GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No./(Center No.) E-19-616 (R6263-0A0) GTRC/~~GIT~~ XX DATE 5 / 14 / 87

Project Director: J.D. Muzzy School/Lab ChE

Sponsor: Lockheed-Georgia Company

Agreement No.: P.O. # RF28615; Subcontract # 01-87-195 (under Prime F33615-86-C-5008)

Award Period: From 1/27/87 To 8/11/89 (Performance) 8/11/89 Reports

Sponsor Amount: New With This Change / Total to Date

Contract Value: $ ______ $ 89,880

Funded: $ ______ $ 60, 214 (Phase I)*

Cost Sharing No./(Center No.) F6263-0A0 Cost Sharing: $ 1,095 (Phase I) ($4,658 Total)

Title: Manufacturing Science of Complex Shape Thermoplastics

ADMINISTRATIVE DATA

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Military Security Classification: unclassified
(or) Company/Industrial Proprietary: N/A

ONR Resident Rep. is ACO: ______ Yes X No
Defense Priority Rating: DO-A1

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed or anticipated

COMMENTS:

*Phase I only is authorized for the period ending 6/14/87.

MAY 1987 RECEIVED

SPONSOR'S I.D. NO. 02.261.000.87.003

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SR-73

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 04/19/90

Project No. E-19-616 Center No. R6263-0A0

Project Director MUZZY J D School/Lab CHE

Sponsor LOCKHEED AERONAUT SYS CO-GA/

Contract/Grant No. RF28615 Contract Entity GTRC

Prime Contract No. F33615-86-C-5008

Title MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Effective Completion Date 890912 (Performance) 890912 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	Y	
Other	N	

Comments

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

NOTE: Final Questionnaire sent to PDPI.

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF TEXTILE ENGINEERING
ATLANTA, GEORGIA 30332
(404) 894-2490

May 7, 1987

MEMORANDUM

TO: Ancil Kays
Lockheed-Georgia Company

FROM: Wayne Tincher
School of Textile Engineering
Georgia Institute of Technology

SUBJECT: Monthly Status Report F33615-86-C-5008

The small sample (~2 pounds) of PEEK powder air mill ground at Georgia Tech has been used to begin initial studies on the rennovated laboratory electrostatic fluidized bed fiber coating line. Brief drying of the PEEK powder in an oven prior to loading in the bed gave excellent fluidization. In trial runs, 50% pick-up by weight of PEEK on carbon fiber was easily achieved.

Modifications to the coating line have been directed toward improved control of resin desposition on the fiber. A new fluidized bed vibration system, improved bed air flow control, improved humidity control in the bed air supply, and a modified tow spreading system have been added to the line. The only element not yet in place is a flow measurement system for the bed exhaust line. These changes should give much better characterization of the bed operational parameters.

Initial runs have suggested one other line modification to improve incorporation of stray filaments into the fiber bundle. As with all carbon fiber handling, broken filaments are present in the fiber bundle and a means to better incorporate these filaments in the bundle is being investigated.

A large sample (30 pounds) of PEEK has been shipped to Plastimer Division of Garlock Incorporated in Newton, Pennsylvania, for commercial air mill grinding. Grinding was delayed until a Material Safety Data sheet could be obtained from ICI but the ground powder is expected to be shipped early in May.

Other activities in May will include completion of the exhaust handling system for the fludized bed and a series of test runs to document effects of experimental parameters on resin deposition on the fiber. Samples will also be prepared for initial characterization by thermal analysis.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 2

May, 1987

Prepared For

Lockheed-Georgia Company

Marietta, Georgia

Prepared by:

J. D. Muzzy

Project Director

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

The Georgia Tech subcontract on this program was initiated January 27, 1987; however, a fully executed contract was not completed until May. Report No. 1 summarizes earlier progress.

There are two major thrusts for the Georgia Tech program: (1) the development of an electrostatic fluidized bed process for producing flexible prepreg and (2) the development of material and process models for thermoplastic composite processing. Both areas were investigated during May.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating

The fluidized bed process was reassembled and processing trials were initiated late in April. The pickup of PEEK 150 powder was varied from less than 10 volume % to over 50 volume % by varying the yarn speed. Since 40 volume % PEEK is preferred, this composition was studied in detail.

The unsized 3K AS4 tow has loose ends as it enters the fluidized bed zone. These ends are attracted to the charged fluidized bed and tend to pick up a higher percentage of the PEEK powder. This tendency leads to a coarse towpreg, axial variations in powder pickup and a preferance for surface coating rather than tow penetration. The tow spreading system was modified in order to minimize this tendency to have loose fiber ends. We concluded that the loose or broken fiber ends are present in the tow and are not necessarily due to the tow spreading operation. Alternative yarns will be sought which have fewer broken ends.

The suface uniformity of the towpreg was improved by inserting a roller in the oven. The hot roller forced the loose ends to contact the main body of the molten towpreg reducing the surface roughness.

The towpreg has been produced in sufficient quantity to permit production of small unidirectional composites. The procedures for consolidating these samples will be resolved during June.

The air milled powder sample prepared at Georgia Tech has been depleted. The 30 pounds of milled powder prepared by Garlock, Inc. has been shipped and is expected shortly. This powder batch has somewhat smaller particle size and is expected to perform better than the batch we have been using.

2.2 Process Modeling

The major need for model development at this time is for rheological data. This data has not been provided by the University of Akron as stipulated in the contract.

A meeting was held at Wright Paterson AFB on May 5 to review modeling requirements. A summary of this meeting is being prepared by Matt Pursley.

We are exploring new approaches for modeling the consolidation and flow data generated by Arif Butt at Georgia

Tech. Preliminary calculations indicate that consolidation and flow can be well represented by an effective viscosity and an effective shear rate that are approximately constant during most of an isothermal consolidation experiment. This analysis will be illustrated in next month's report.

3.0 Problems

The major difficulty we are encountering at this time is a lack of data from the University of Akron.

4.0 Planned Activities for Next Report Period

We will initiate powder impregnation studies using the new powder batch from Garlock, Inc. We will conduct characterization studies on this new batch in powder form and as prepreg in order to arrive at suitable conditions for producing the quantities of prepreg required in Phase I. Samples of this prepreg will be delivered to the University of Akron for characterization. We will continue model development as fast as data arrives.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 3

June, 1987

Prepared For

Lockheed-Georgia Company

Marietta, Georgia

Prepared by:

J. D. Muzzy

Project Director

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major thrusts for the Georgia Tech program: (1) the development of an electrostatic fluidized bed process for producing flexible prepreg and (2) the development of material and process models for thermoplastic composite processing. Both areas were investigated during June.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating

The processing line was used to process other materials, cleaned and then converted to a larger fluidized bed during June. The large bed, 14"x16", will permit processing more yarns in parallel. A filter bag was installed for collecting and recycling overflow powder. A 50 gram sample of the PEEK powder from Garlock, Inc. was forwarded to Lockheed-California for size analysis.

The PEEK towpreg has been characterized by DSC and SEC. The DSC heating scan exhibits both crystallization and melting, indicating that the PEEK did not fully crystallize in processing. The DSC cooling scan at $10^{o}C/min$ was quite similar to cooling scans on APC2. This similarity indicates the PEEK has not been degraded due to milling and coating. Also, the results suggest surface nucleation of spherulitic structures may be occurring. SEM photographs indicate very good wetting of the AS4 fiber by PEEK.

PEEK towpreg was cut into 1½" long strips and placed in a parallel arrangement in a 1" wide matched die mold. The strips were consolidated at 720°F and 100 psi for 5 minutes and then cooled under pressure. The surfaces of the sample indicate that some of the tows were misaligned during layup or consolidation; hence, the sample is not completely unidirectional. There is also evidence of resin squeeze out at the fiber ends. The sample has been delivered to Lockheed-Georgia for microscopic examination.

2.2 Process Modeling

Rheological data on neat PEEK and PAS2 arrived from the University of Akron at various times during June. The digital data on floppy disk had not arrived by the end of June but it is expected. Examination of the graphical data on PEEK does not indicate a very good overlap between the capillary rheometer data and the dynamic mechanical rheometer. The PAS2 data may exhibit better overlap. This issue can be addressed quantitatively once all the data is collected on the VAX at Georgia Tech. For PAS2 at 340 and 360°C there was a distinctive increase in viscosity when a second frequency sweep was made. This increase in viscosity with time at temperature requires additional characterization which the University of Akron is pursuing.

Only conceptual process modeling was performed during June since the rheological data base was not available. Since data have arrived process modeling can proceed during July.

3.0 Problems

Additional rheological data is still needed to effectively develop the consolidation model. Since PAS2 exhibits a viscosity increase with time at temperature and apparently produces volatile byproducts above 310°C, a more complex experimental plan as well as a more complex consolidation model may be necessary.

4.0 Planned Activities for July

The electrostatic fluidized bed coating process will first be operated to establish preferred operating conditions using the larger bed, the powder from Garlock, Inc. and two tows running simultaneously. As soon as appropriate conditions are established to give approximately 60 volume % fiber with good tow penetration, then sufficient sample will be produced for fabric production. With these samples final arrangements will be made for producing fabric. Samples of the towpreg will be characterized by DSC and SEM. Also small unidirectional samples of towpreg will be consolidated and characterized.

Process modeling will be pursued during July using the data base from the University of Akron.

Progress will be presented at the quarterly review meeting scheduled for July 21st at Wright-Patterson AFB.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 4

July, 1987

Prepared for

Lockheed-Georgia Company

Marietta, Georgia

Prepared by:
J.D. Muzzy

Project Director

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major thrusts for the Georgia Tech program: (1) the development of an electrostatic fluidized bed process for producing flexible prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating

Due to scheduled maintenance entailing replacing the floor in the lab containing the processing line, it was not possible to operate the electrostatic fluidized bed process during July. Therefore we focused on characterizing towpreg samples produced earlier.

The initial characterization of the towpreg performed at Georgia Tech includes:

- resin content
- microscopy
- DSC
- consolidation
- bending

The resin content is determined by weighing measured lengths of tow before and after coating. Microscospy is performed to qualitatively evaluate fiber wetting and resin distribution throughout the tow before and after consolidation. The consolidated samples are also examined for void content and fiber alignment.

DSC scans are used to characterize crystallinity, fiber nucleation of crystallization and potential degradation. For example, the crystallinity of the towpreg is less than 20%, corresponding to a quench rate around 1,000^{o}C/min. The towpreg exhibits additional crystallization upon heating. Fiber nucleation can be ascertained by the peak crystallization temperature upon cooling a sample in the DSC. For a cooling rate of 10^{o}C/min APC 2 exhibits at peak near 298^{o}C whereas PEEK 150 exhibits a peak near 293^{o}C. We have produced towpreg with a peak crystallization temperature near 298^{o}C which is indicative of fiber nucleation of crystallization. Degradation can be detected by reductions in crystallinity and crystallization rate. Such degradation is not apparent in the towpreg.

A matched die mold is used to consolidate towpreg. The layup is performed by aligning 1 1/2" long strips in either a 1/4" or 1" wide cavity. The heating and cooling rate is 10^{o}C/min. The peak molding temperature is 380^{o}C. The peak molding pressure is 100 psi. The time at 380^{o}C is being assessed. The sample thickness is continuously monitored to provide a future basis for determining on-line when to start cooling.

Aside from the microscopic examination of consolidated laminates, these samples will be subjected to flexural testing. Some of these consolidated samples will be sent to the University of Akron for more extensive mechanical testing.

During July a number of samples were molded and are currently being characterized by microscopy. One set of samples was molded to provide 5 mil thick samples for direct comparison with APC 2 prepreg. The consolidation time at 380^{o}C was less than 5 minutes. The fiber wetout in these samples appears to be very good.

2.2 Process Modeling

Rheological and crystallization data from the University of Akron has been received and added to the data file on the VAX at Georgia Tech. The quality of this data was reviewed with the University of Akron on July 20th. Specific issues discussed were the need for reported experimental methods and observations, the need to obtain low shear rate nonisothermal data, the need to resolve viscosity changes with time, particularly for PAS 2, and the need to resolve discrepancies between capillary rheometer and DMA viscosities. These discrepancies are evident in Figures 1 and 2 which show much higher viscosities and much greater temperature sensitivity in comparing capillary data to DMA data. It was decided to ignore the capillary flow data for now and rely on the unidirectional shear rheometer to resolve which set of data should be used in the long run.

Mr. Drew Mallow of the McDonnel Aircraft was forwarded PEEK 150 viscosity data collected for the Processing Science program. This data was also collected by DMA and is close to the DMA data collected by the University of Akron. This data will also be used to construct the rheological model.

The composite flow data collected by Mr. Arif Butt for his Masters thesis at Georgia Tech has been analyzed in terms of apparent viscosity and apparent shear rate as shown in Figure 3. This analysis clearly illustrates that an apparent viscosity model is not adequate for flow analysis in a composite. It is still necessary to consider volume fraction dependent permeabilities or resistances. The apparent shear rate data emphasizes the need to focus on low shear rate data at this time. Since the polymers approach Newtonian behavior at such low shear rates it is appropriate to use a shear rate independent viscosity model for the polymers in the consolidation model at this time.

Mr. Larry Norpoth, as part of his thesis research at Georgia Tech, has illustrated the need to consider elastic recovery effects in APC 2 consolidation. Figure 4 shows the effect of cycling the applied load between 3 and 100 psi. Both an immediate elastic recovery and a delayed elastic recovery can be detected. These effects should be quantified for the consolidation model. This and related issues will be addressed in a separate proposal to the Air Force.

3.0 Problems

The maintenance work in the composites processing lab prevented us from doing any coating in July. This work is complete and we will conduct coating runs at an accelerated rate during August.

The unidirectional shear data requested from the University of Akron has been delayed. This data is needed to confirm modeling assumptions.

4.0 Planned Activities For August

The electrostaztic fluidized bed will be opeated to establish new operating conditions with the larger bed and refurbished components. The powder from Garlock, Inc. will be used as well as running two tows in parallel. Sufficient material will be produced for fabric weaving and fabric preparation will be implemented. Small consolidated towpreg samples will be sent to the University of Akron.

Viscosity versus temperature models will be implemented in the process model. Also the crystallization model will be updated to fit the data from the University of Akron. Fiber network compliance functions and permeabilities will be incorporated in the models based on the best available information.

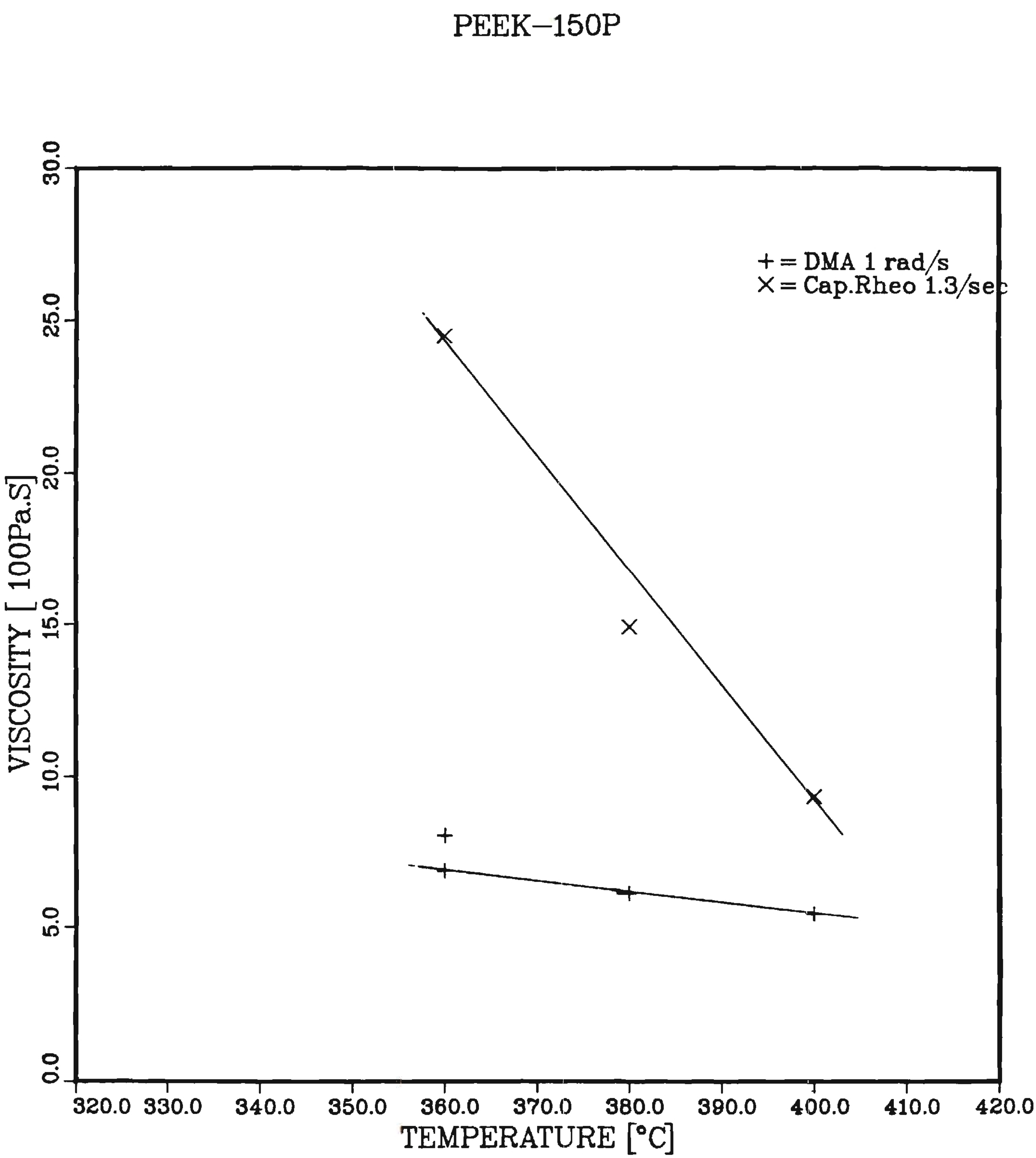

Figure 1 Comparison of viscosity measurements on neat PEEK 150P by capillary flow and Rheometrics DMA at comparable shear rates

PAS 2

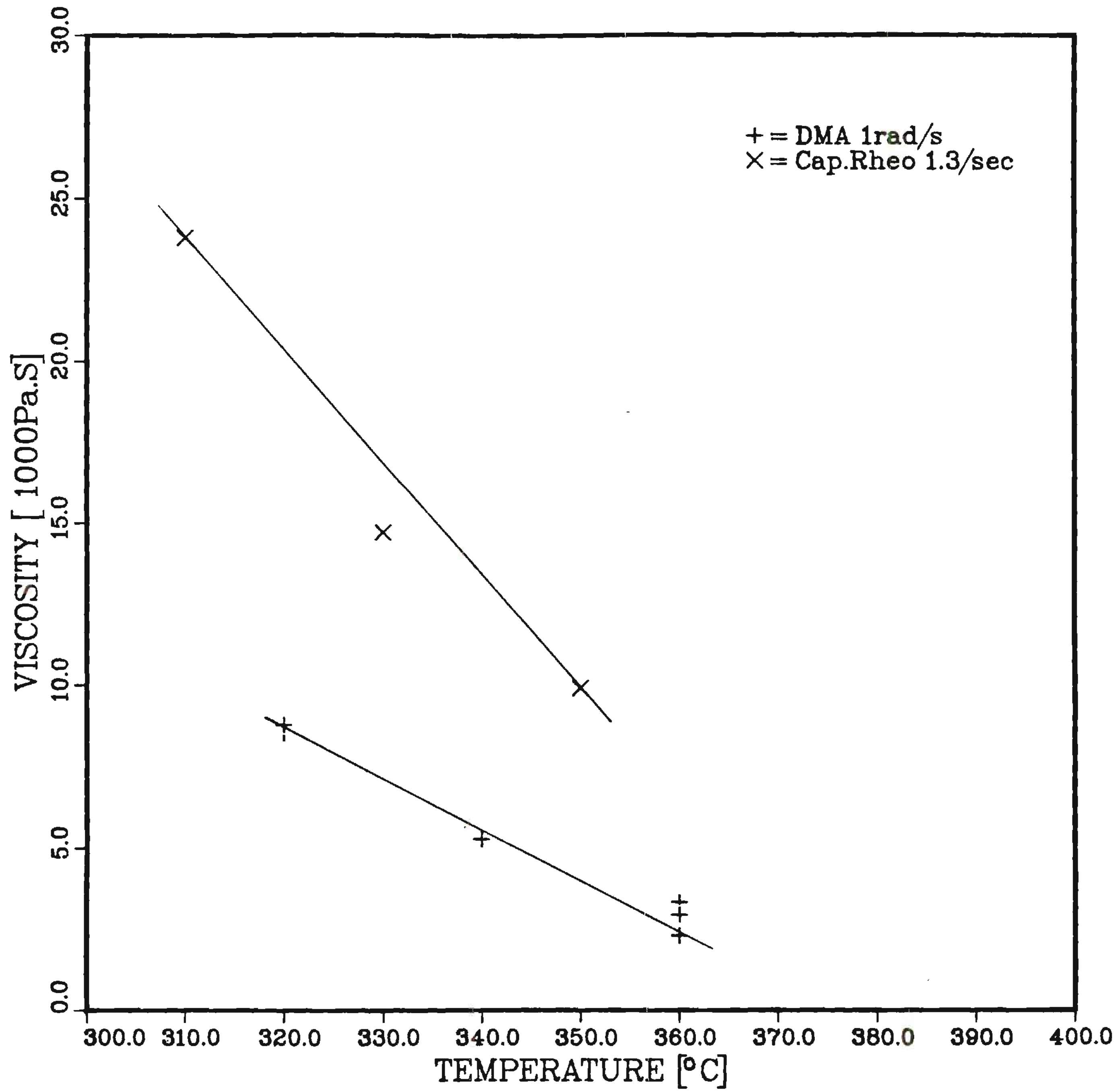

Figure 2 Comparison of viscosity measurements on neat PAS 2 by capillary flow and Rheometrics DMA at comparable shear rates.

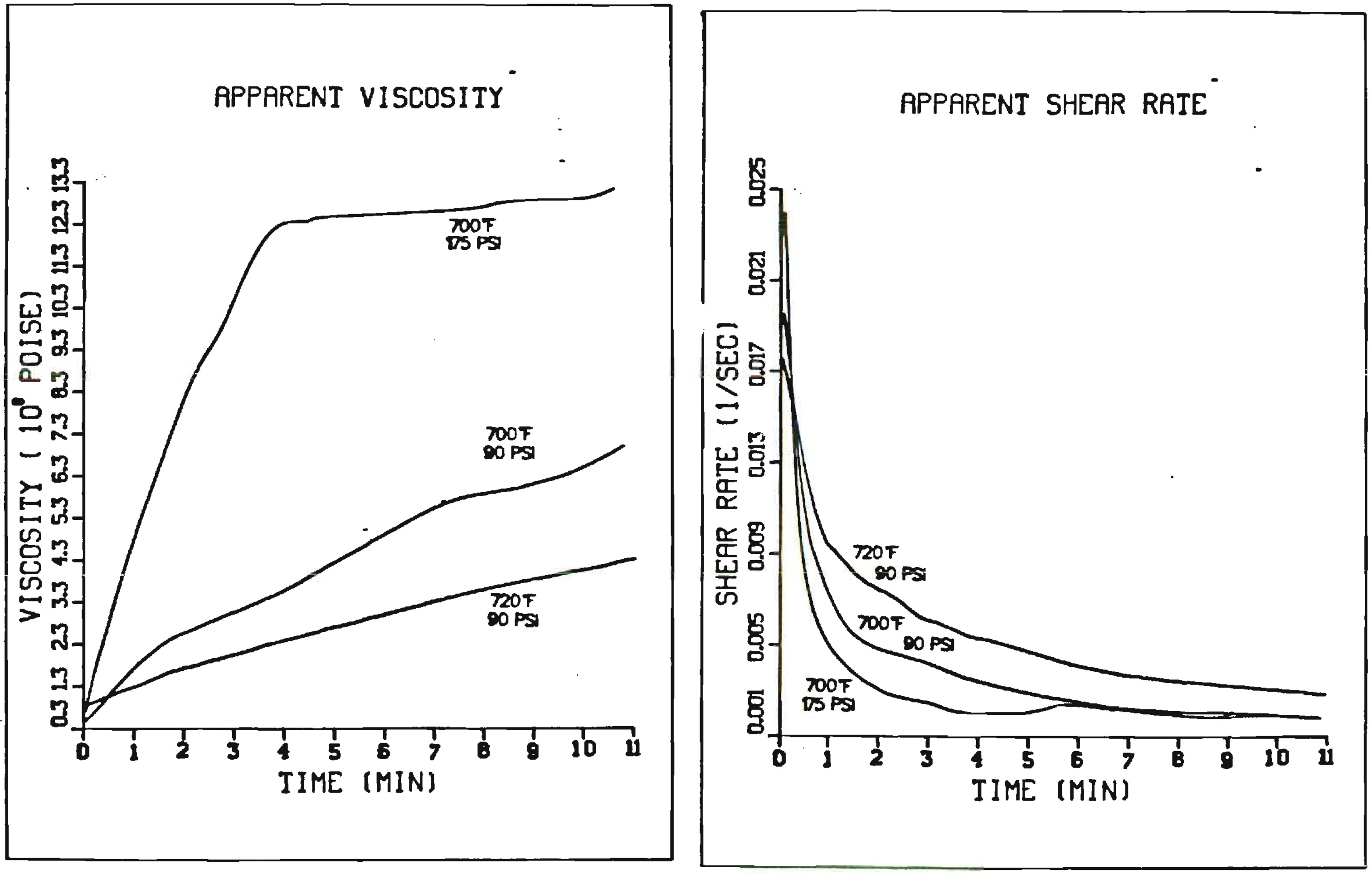

Figure 3 Analysis of unidirectional squeeze flow experiments conducted on a 24 ply APC 2 laminate one inch long in terms of apparent viscosity and apparent shear rate as a function of time after load application.

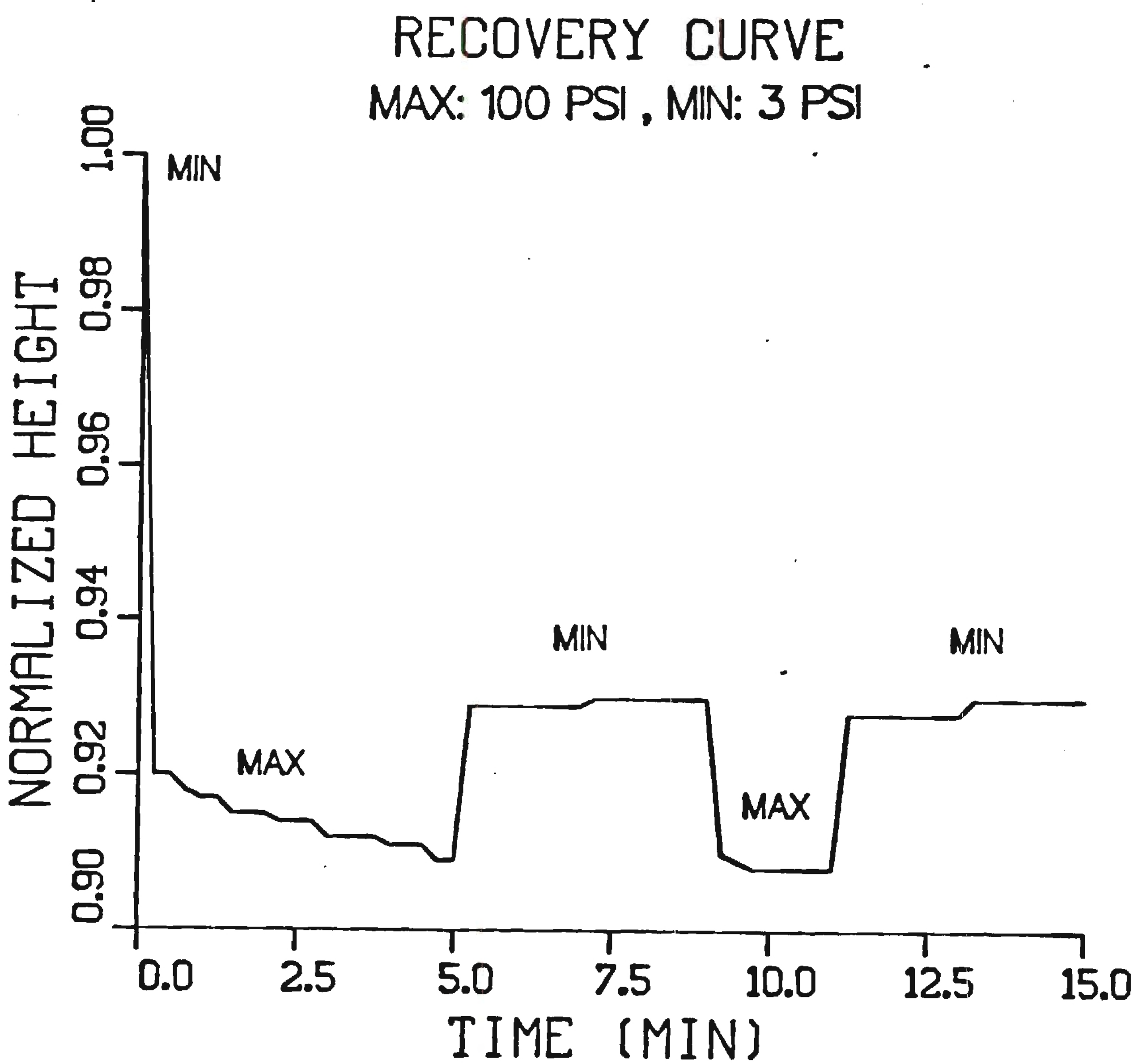

Figure 4 Change in height versus time during the consolidation of 16 unidirectional APC 2 plies 1 1/2" long illustrating the partial recovery of sample height upon applied load reduction.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 5

August, 1987

Prepared for

Lockheed-Georgia Company

Marietta, Georgia

Prepared by:_______________

J.D. Muzzy

Project Director

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major thrusts for the Georgia Tech program: (1) the development of an electrostatic fluidized bed process for producing flexible prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating

New processing conditions have been established for the refurbished larger fluidized bed. The process line was modified to coat two tows simultaneously. Unfortunately the two tows do not spread equally resulting in moderately different coating levels. This difference in spreading can be corrected with modest mechanical modifications of the processing equipment.

Dr. Tincher visited J.B. Martin and Co. in South Carolina regarding converting the coated tow into fabric. After reviewing the weaving process we have decided to prepare Phase I fabric samples at Georgia Tech. We are currently seeking a 400 denier carbon fiber tow to conduct this weaving trial.

2.2 Process Modeling

The rheological data from the University of Akron has been analyzed to obtain temperature dependent melt flow expressions for PEEK 150 and PAS2. Similarly, the squeeze flow and consolidation experiments conducted by Mr. Arif Butt for his Master's thesis at Georgia Tech have been evaluated to determine a consolidation constant, C, and an axial flow constant, k, for APC2. In lieu of additional data C and k will be assumed to be constant. The values of these rheological constants will be presented in the Phase I report as well as the methodology used to obtain these parameters and the validity of the rheological models.

3.0 Problems

We will be unable to produce fabric by the end of Phase I. This delay is due to the replacement of the floor in the processing lab which interfered with the production of coated tow for fabric formation. The fabric samples will be produced late in September and early in October provided the 400 denier tow is obtained by that time.

The rheological modeling has advanced to the stage where process simulations can be performed. These models will need refinement in Phase II. Additional data was received from the University of Akron by the end of August; but, there has not been time to evaluate this data. The unidirectional shear data, which was requested last February, has not been received from the University of Akron.

4.0 Planned Activities

Sufficient coated tow will be produced before the conclusion of Phase I to meet the requirements for this Phase. Unidiectional bars will be molded from these pilot samples for evaluation.

The rheological models will be extended to consider shear rate effects as well as the intermediate temperature range between melt processing and solidification. The progress during Phase I on electrostatic fluidized bed coating and on material modeling will be reviewed in the Phase I report.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 6

September, 1987

Prepared for

Lockheed-Georgia Company

Marietta, Georgia

Prepared by: ______________________

J.D. Muzzy

Project Director

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major thrusts for the Georgia Tech Program: (1) the development of an electrostatic fluidized bed process for producing flexible prepreg and (2) the development of material and process models for thermoplastic composite processing.

Most of the work on these tasks has been incorporated in the Phase I report. The following report focuses on activities for the last two weeks in September.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating

The 400 denier yarn ordered from Heltra, Inc. has arrived (1/2 lb Grafitex SX2-400). This yarn will be used in weaving the PEEK tow. A special loom has been ordered to accomplish the weaving.

A new mold insert has been designed and is in construction for preparing unidirectional laminates of the towpreg. The design of this new mold was discussed in the Phase I report.

Towpreg production for weaving is ready to start. Before running the process line to meet the fabric needs we want to do final quality control checks on the tow.

2.2 Process Modeling

The modeling is discussed in detail in the Phase I report. We have been attempting since mid-September to improve the Carreau model for PEEK 150. We have also reviewed the rheological data sent from the University of Akron. It is apparent that it will be necessary to change the constants in the Carreau model based on this last set of results.

3.0 Problems

We are behind schedule on producing tow and fabric from the electrostatic coating process. We are focusing on this task in order to catch up.

4.0 Planned Activities

Our primary focus during October will be on producing, characterizing and weaving tow. We will also develop a quantitative analysis of the last set of rheological data from the University of Akron.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 7

October, 1987

Prepared for

Lockheed-Georgia Company

Marietta, Georgia

Prepared by:__

J.D. Muzzy

Project Director

November 6, 1987

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

The primary task of producing enough towpreg for weaving was accomplished. The processing conditions for this task are presented in Table 2.1-1 under run number 10-1. This tow is 5 mils thick and about 1/4 inch wide. The 3K tow splits into two primary plies. Each ply is substantially bonded even though tow spreading rollers were placed immediately after the oven in order to keep fibers separated. The driven pinch rolls contacted cold tow in order to prevent further consolidation. Consolidated tow is stiffer and therefore harder to wind. The tow passed over flexible foam brushes in order to remove loose hairs from the tow.Smaller quantities of sized tow were produced at the conditions presented in Table 2.1-1 under runs 10-2 and 10-3. The primary operating difference between these two runs is the elimination of tow spreading in run 10-3. Without tow spreading an essentially round tow is produced. This tow passed over a grooved teflon wheel to promote shaping and consolidation. Since the tow was not spread and the tow was partially consolidated, it was not necessary to brush off loose ends. The handling of these two sized tows in weaving is expected to be considerably different.

2.2 Material and Process Modeling

The focus in modeling during October has been on developing a correlation between resin viscosity and composite viscosity in undirectional drag flow. The composite viscosity is not a true viscosity because the imposed shear rate is not the resin shear rate. As a first approximation this relationship is

$$\dot{\gamma}_c = V_r \dot{\gamma}_r$$

where

$\dot{\gamma}_c$ = composite (sample) shear rate

V_r = volume fraction resin

$\dot{\gamma}_r$ = resin shear rate

In addition to this shear rate difference there is an additional resistance associated with the added surface area due to the presence of the fiber. This additional resistance to flow should be a geometric constant dependent on the direction of flow. In sum, an approximate relationship between shear stress and shear rate takes the form

$$\tau = g\eta\dot{\gamma}_c/V_r$$

where the new terms are:

τ = shear stress

g = geometric constant

η = resin viscosity

On this basis the unidirectional viscosity data obtained on the MER-1100A by the University of Akron is being analyzed. A preliminary evaluation indicates g is in the range of 10 and is smaller for flow perpendicular to the fiber axis.

The shear rates imposed by the MER-1100A are high for composites processing. The ability to collect viscosity data at lower shear rates will be discussed with the University of Akron.

3.0 Problems

It would be beneficial to meet with the University of Akron to review experimental data and future experimental needs.

4.0 Planned Activity

A significant portion of our time during October has been devoted to updating Phase II plans. These plans are discussed below. During November, we will focus on making fabric from the EFBC towpreg just produced. In the modeling area we will refine the analysis of unidirectional drag flow and start on extending the viscosity model to lower temperatures.

4.1 Electrostatic Fluidized Bed Coating Phase II Plans

A task schedule is presented in Figure 4.1-1. A brief description of each Phase II subtask is presented below.

The materials to be produced during Phase II include 10 pounds of PEEK 150/ AS4 towpreg containing 40 volume % PEEK (task 4.2.1.), 10 pounds of PEEK 150/AS4 sized tow containing 10 volume % PEEK (task 4.2.1.2) and 20 pounds of fabric from the towpreg and sized tow. Due to the substantial amount of fabric required a commercial weaver will be used to produce the fabric. Since we are converting the Phase I towpreg into fabric similar to the structures developed by J.B. Martin Co., we will consider J.B. Martin first for accomplishing this task. The proposed fabric structure at this time is bidirectional noninterlaced PEEK towpreg with a 400 denier carbon binder yarn in the warp direction. 18 pounds of the fabric will be delivered in April to the University of Akron for forming studies (task 4.2.1.4). The remainder will be used at Georgia Tech for characterization.

The characterization of towpreg has been described in the Phase I report. Towpreg produced during Phase II will be characterized in the same manner (task 4.2.2.1). Sized tow will be characterized in the same manner except PEEK powder will be added during consolidation to produce 40 volume % PEEK laminates (task 4.2.2.2). In task 4.2.2.3 4"x4" fabric plies will be molded into laminates and characterized to establish appropriate consolidation conditions.

A model of the electrostatic fluidized bed coating process will be developed during Phase II. This task has been split into three parts: electrostatic fluidized bed coating (task 4.2.3.1), the melting and wetting which occurs in the oven (task 4.2.3.2) and the influence of multiple tows (task 4.2.3.3). The influence of multiple tows is an important consideration in scaling the process to suit commercial production rates.

4.2 Material and Process Model Phase II Plans

Material and process model development in Phase II is part of Task 4.2.4: Consolidation and Forming. A subtask schedule is presented in Figure 4.2.1. Most of these subtasks are described briefly below. Two of the subtasks, 4.2.4.1.4: Validation of Consolidation and 4.2.4.2.3.: Forming Model Validation, will require additional funding for Georgia Tech. Therefore the experimental plans for these subtasks are presented in more detail. The cost for this additional work is presented in a separate letter to Ancil Kays.

The interaction between structure, properties and processing is illustrated in Figure 4.2-2. The structural state submodels establish the transport and deformation properties which are necessary to implement the process simulations for consolidation. The process simulations are used to update the structural state of the composite which reflects the extent of consolidation. For convenience the task schedule only lists processing phenomena. As these processing phenomena are developed the necessary structural features and processing properties will be covered.

4.2.4.1.1. Heat Transfer.

Due to the high processing temperatures and rapid processing rates under consideration for the thermoplastic composites it is necessary to refine estimates of thermal properties. The thermal properties of greatest concern are specific volume, heat capacity and thermal conductivity. We will focus on representing the temperature dependence of thermal properties for the materials listed in Table 4.2-1. The property data will be sought from the suppliers, publications, the University of Akron and task 4.2.4.1.4. Although some of the ply materials are comprised of similar materials it would be beneficial to check heat conduction through the porous plies.

4.2.4.1.2 Elastic Deformation.

The current simulation includes an expression from Gutowski for determining what portion of the applied load is carried by the fiber network. It is preferable to use the compressive modulus of the composite in order to determine overall composite height as well as the pressure in the resin. The composite compressive modulus depends on ply structure and composition. Estimates will be made for the plies listed in Table 4.2-1. This task would be facilitated by the validation tests planned for task 4.2.4.1.4.

4.2.4.1.3 Mass Transfer.

An elementary model for mass transfer was implemented in Phase I. The following subtasks will be conducted during Phase II:

- Extend the viscosity correlation to lower temperatures for PEEK 150 and PAS 2
- Model the influence of crystallinity on the viscosity of PEEK 150
- Develop a correlation between composite and neat resin viscosity data
- Interpret the directional viscosity dependence obtained by the University of Akron for APC 2 and PAS 2 unidirectional composites
- Develop a kinetic expression for the time dependence of PAS 2 viscosity
- Add elastic component models for APC 2 and PAS 2
- Resolve data discrepancies between different rheometers used by the University of Akron

The data has been sent by the University of Akron so these subtasks will be addressed early in Phase II. The following subtask will require new data from the University of Akron:

- Develop a viscoelasticity model for Cypac 7005

The mass transfer simulation requires coefficients for consolidation, adhesion, wetting and flow. The following subtasks are proposed:

- Refine the consolidation and flow coefficients to suit the ply geometries to be used during Phase II
- Develop adhesion and wetting coefficients

These subtasks would be greatly facilitated by proposed subtask 4.2.4.1.4: Validation of Consolidation. Springer's autohesion model will be evaluated in conducting this work.

4.2.4.1.4 Validation of Consolidation

This subtask is a proposal for additional work to be performed at Georgia Tech. Figure 4.2-3 lists the experiments planned. All the materials listed in Table 4.2-1 for Phase II are included in the study. The effect of changes in the number of plies, ply structure, layup sequence, temperature, pressure and time are all considered in the plan. Special test features are incorporated in order to evaluate network elasticity, ply adhesion, specific volumes and thermal conductivities.

A new consolidation tester has been constructed for this subtask. This tester has the following features.

- 4" x 4" sample area
- Programmed temperature control
- Programmed load control (Instron)
- Programmed displacement control (Instron)
- Resin pressure sensor
- Multiple temperature sensors
- Accurate displacement sensor
- Vacuum degassing

This tester is an improved version of Butt's smaller tester which was used to obtain the consolidation coefficient and flow coefficient estimates in Phase I. The new tester has additional sensors for continuously monitoring the progress of consolidation. Since the sample size is considerably larger errors due to flashing will be minimized. In addition the consolidated samples are large enough for post consolidation testing. This post consolidation characterization will include

- C-scans
- Mechanical Properties
- Adhesion
- Fractography
- Microdimensions

Finally, the continuouse monitoring of composite temperature, resin pressure, and thickness will be directly compared with consolidation simulations. These results will improve the accuracy and versatility of the consolidation simulation by providing critical experimental validation.

4.2.4.2 Forming Model

The current approach proposed for modeling forming is to establish forming tables which would describe the quality of forming achieved using specific processing conditions, materials and tooling. Thermoplastic composites tend to deconsolidate at forming temperatures. Also the possibility of combined consolidation and forming will be investigated. For these reasons an analytical model of forming, similar to the consolidation model, warrants investigation. Most of the structure, property and processing submodels for consolidation are needed for forming. Figure 4.2-4 illustrates the projected additional components to achieve a combined consolidation/forming simulation. The additional structure-property information is not great since most of this information is in the consolidation simulation. Furthermore, the additional forming property information can be estimated. Therefore the primary subtasks entail formulating and validating the forming process model.

The subtasks listed in Figure 4.2-1 for forming are literature review, model development and model validation. Since this last task is a proposal for additional work it will be discussed in some detail.

The validation program consists of mechanical testing and forming trials in a high temperature oven in an Instron testing machine. The test fixtures include flexure, shear and tension. The forming tool is a matched die mold which replaces contact elements on the high temperature flexure fixture. The mechanical testing permits measuring relevant forming properties at forming conditions and the matched die molding permits meaningful forming trials in a well instrumented environment.

The material to be studied is APC-2/AS-4 unidirectional tape. Other materials are not proposed at this time in order to limit the number of tests. The APC-2/AS-4 layups used by Akron and Superform will be emphasized. Both unconsolidated and consolidated forms will be evaluated. A total of 64 tests are planned including 16 matched die forming trials. The samples will be characterized after testing primarily by photomicroscopy.

4.2.4.3 Review Process Simulations

Lockheed-Georgia will develop specific simulations for the processes under consideration during Phase II. We will provide assistance in reviewing these simulations. Also we will focus on accomplishing our work on the subtasks discussed above in a time frame which is beneficial to Lockheed-Georgia for meeting specific simulation target dates.

Table 2.1-1

EFBC Processing Conditions
for October, 1987
(PEEK 150/3K AS 4)

Run Number	10-1	10-2	10-3
Fluidized Bed Length, Inches	18	18	18
Number of Tows	1	1	1
Tow Spreading	Yes	Yes	No
Tow Velocity, ft/min	10	17.8	17.8
Air Pressure, Psi	85	55	55
Air Flow, SCFH	13	10	10
Voltage, KV	80	50	50
Current, microamps	60	10	10
Oven Temperature, $^{\circ}C$	500	550	550
Ave Powder Size, Microns	50*	50*	50*
Tow Resin Content, Vol %	40+	10*	10*
Tow Height, mils	5	5*	15
Tow width, mils	250+	250+	15
Amount Produced, grams	2090	219	129

*Estimated

Table 4.2.-1

Phase II Materials

Neat Resins	
	PEEK
	PAS 2
	Cypac 7005
Fibers	
	AS 4
Plies	
	APC 2 Tape
	APC 2 Braid
	Comingled PEEK
	PEEK Towpreg Fabric
	PAS 2 Tape
	Cypac 7005 Tape

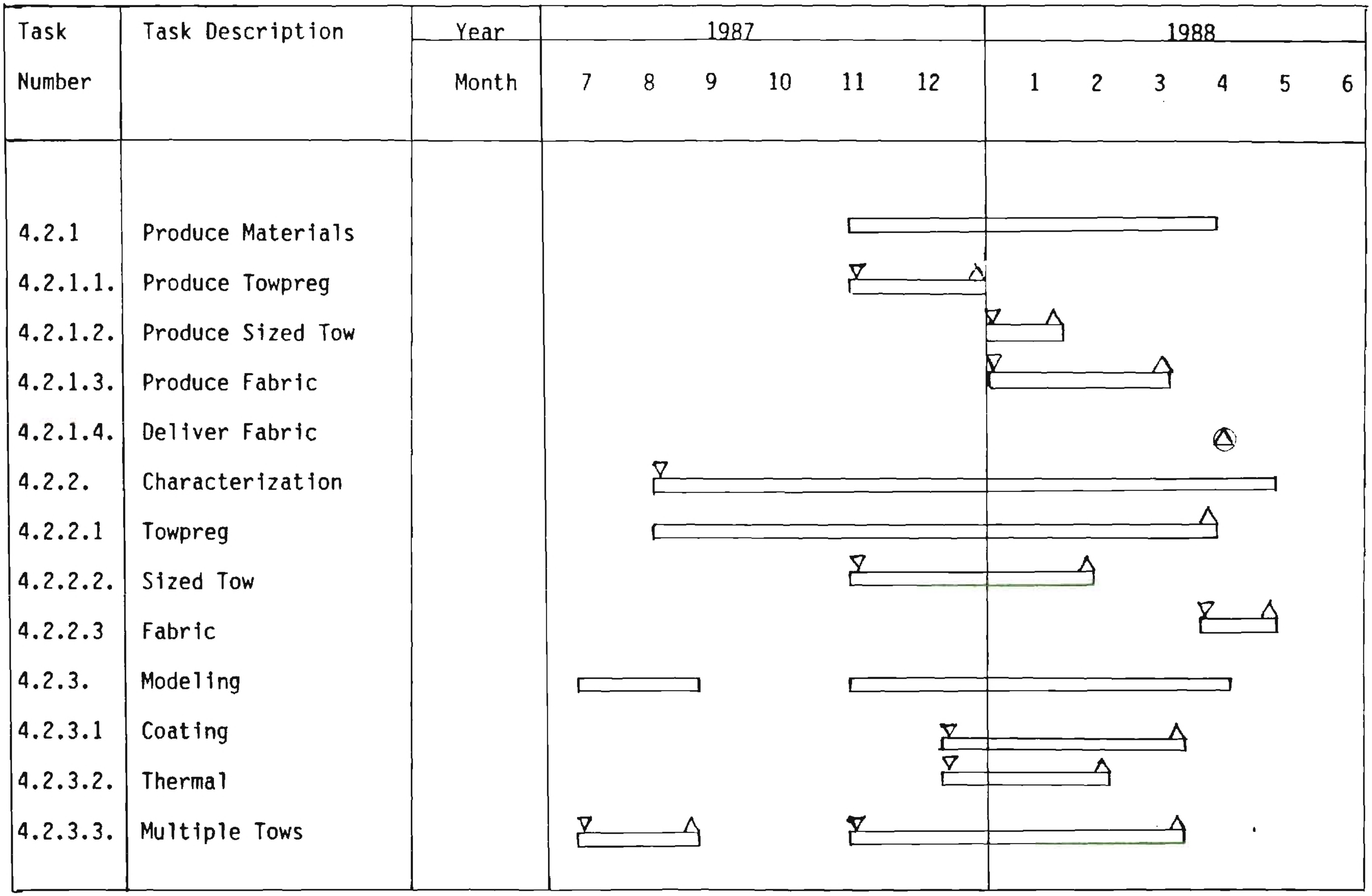

Figure 4.1-1. Phase II Task Schedule for Electrostatic Fluidized Bed Coating Process

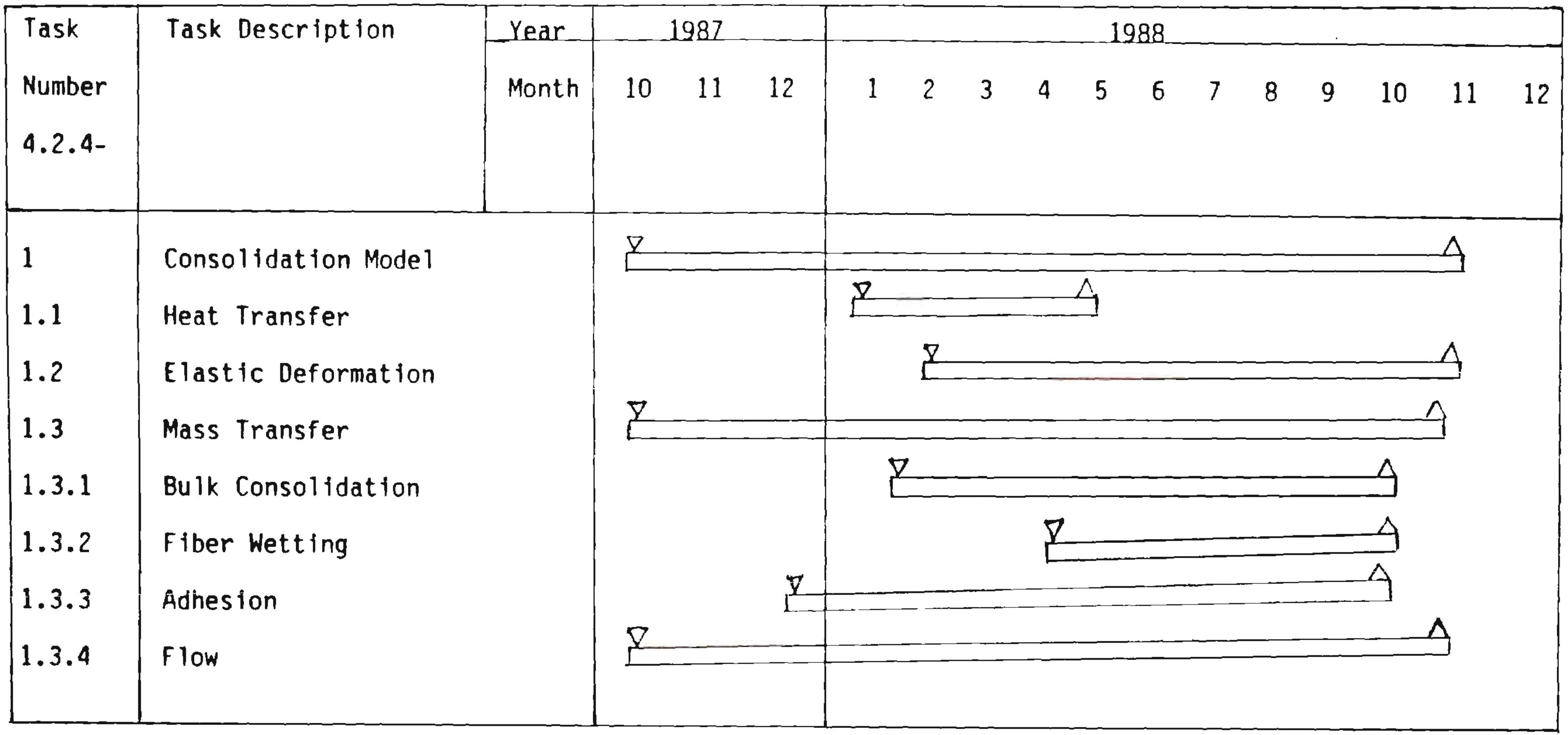

Figure 4.2.-1. Phase II Subtask Schedule for Task 4.2.4, Consolidation and Forming - 1/2

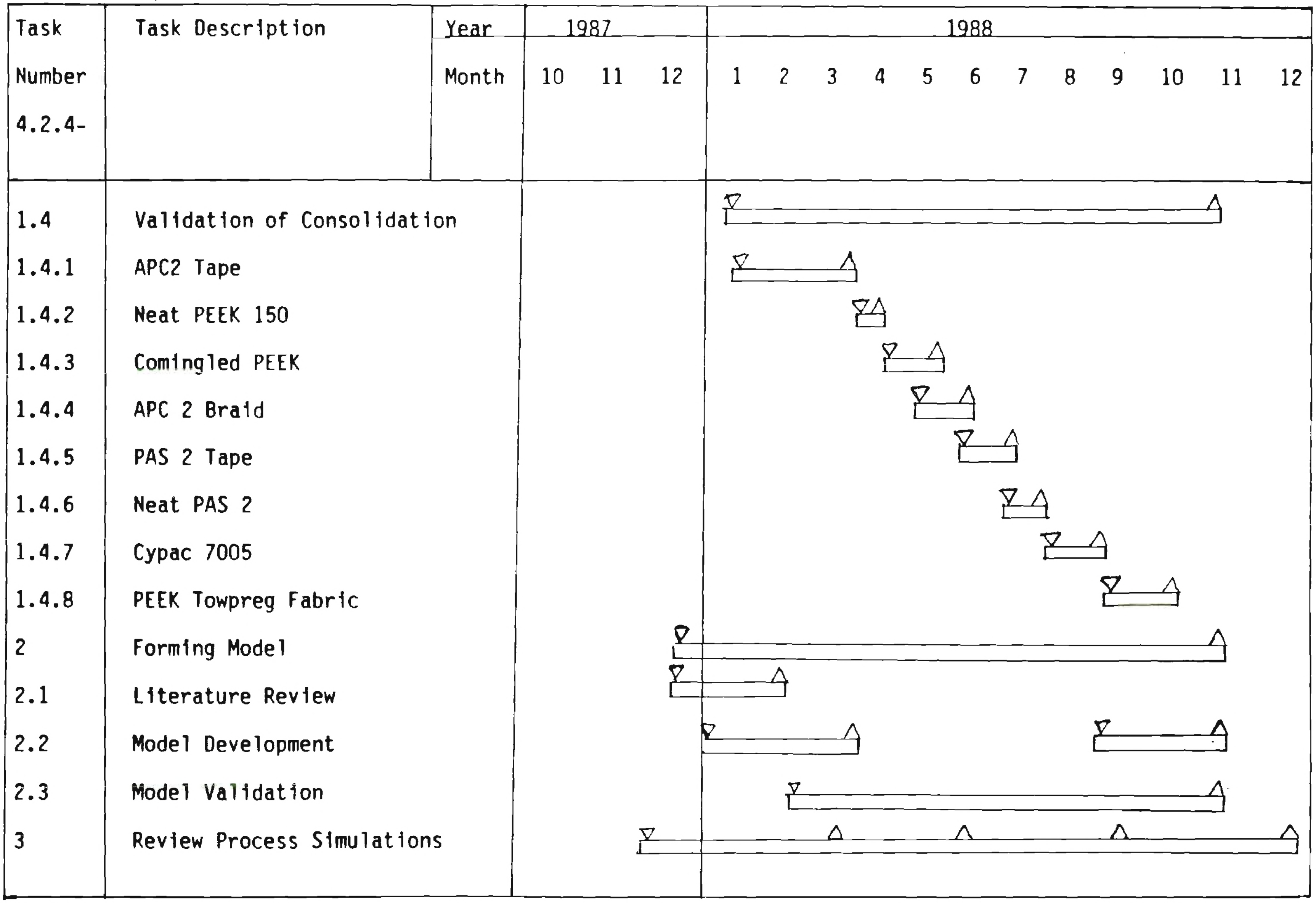

Figure 4.2.-1 Phase II Subtask Schedule for Task 4.2.4, Consolidation and Forming - 2/2

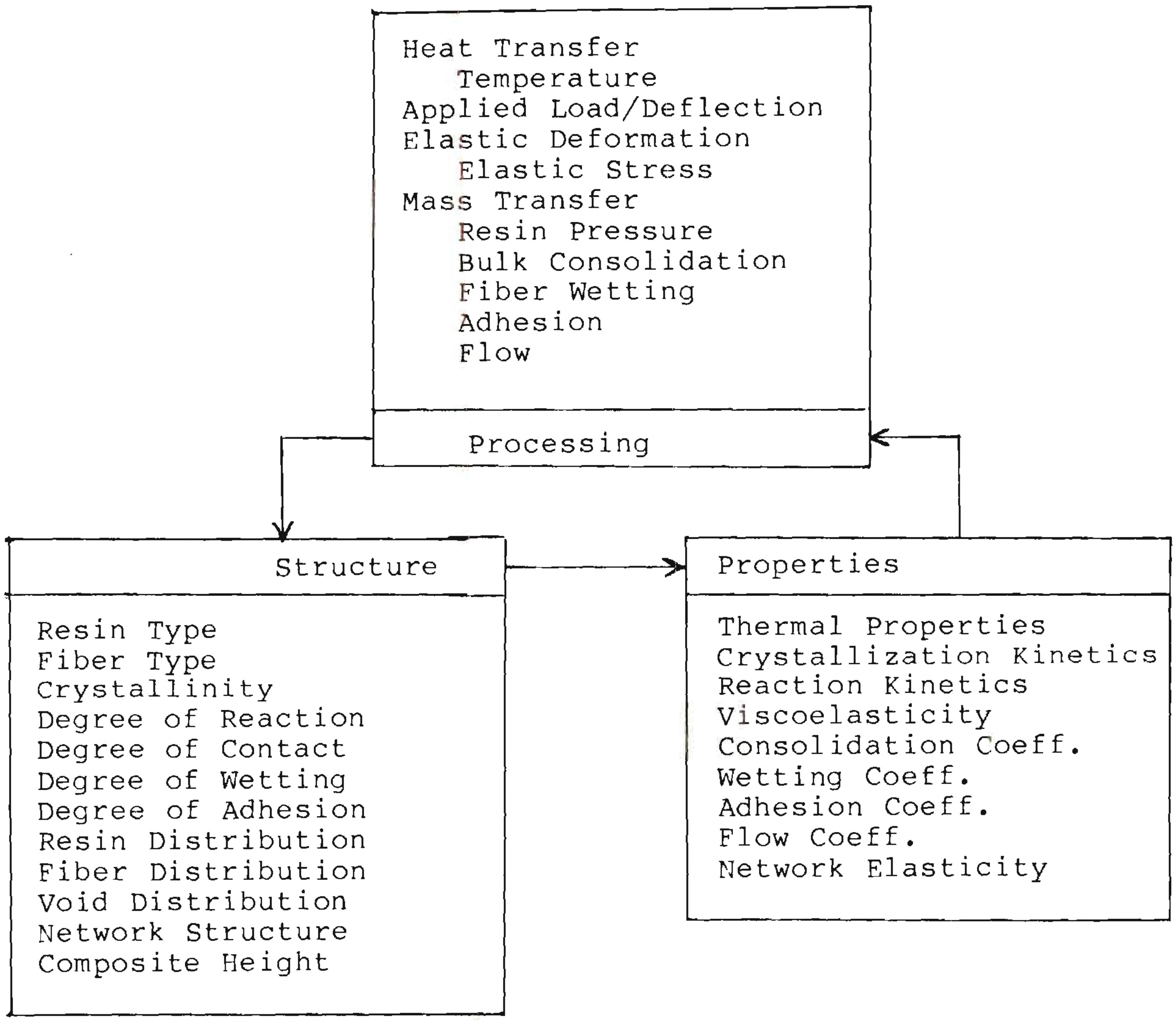

Figure 4.2.-2. Components of the Composite Consolidation Simulation

No.	Material	Plies N	Layup θ_N	Temp $T, ^{o}F$	Pressure P,PSI	Time @ T_{max} t,min	Special Test Feature	Comments
1	APC 2	16	UD	720	100	10		Standard cycle
2	Tape	4						Effect of No. of Plies
3		8						
4		32						
5		64						
6		16		700				Effect of Temp
7				740				
8				720	150			Effect of Pressure
9					50			
10					100	2		Effect of Time
11						20		
12						10	Ramp P at	Characterize
13							Various stages	Network and
14							after consolidation	Polymer Elasticity
15								
16			Preconsol		5			Measure v_m, v_k
17			UD		20			and k
18					50			
19					100			
20			0/90					Effect of 0/90
21							Ramp P	
22			Quasi-iso					Effect of Quasi-
23							Ramp P	isotropic
24				700				
25				740				

Figure 4.2-3. Proposed Consolidation Tests - 1/3

No.	Material	Plies N	Layup θ_N	Temp T, °F	Pressure P, PSI	Time @ T_{max} t, min	Special Test Feature	Comments
26	APC		UD			5	Kapton Inserts	Evaluate Ply
27	Tape					10	" "	Adhesion
28						20	" "	
29			0/90			10	" "	
30						20	" "	
31	Neat PEEK	1/4"	full	720	5	5	Operate as a	Measure v_m
32	150		cavity		10	5	Dilatometer	
33	Comingled	8	UD		150	20		
34	PEEK					10		Comingled
35					100			Prepreg
36			0/90				Ramp P	Evaluation
37							Ramp P	
38					150	20		
39	APC 2	16	$\pm\theta^o$		100	10		Braided
40	Braid						Ramp P	Fabric
41			$90^o\pm\theta^o$				Ramp P	Evaluation
42		8				20		
43								
44	PAS 2	16	UD	650		10		
45	tape			620				PAS 2
46				680				Evaluation
47				650		5	Kapton Inserts	
48						10	" "	
49						20	" "	
50			Preconsol		5		Ramp P	
51			UD		20		" "	
52			0/90		100		" "	
53			Quasi-iso				" "	
54	Neat	1/4"	full		5	5	Operate as a	Measure PAS 2 v_m
55	PAS 2		cavity		10	5	dilatometer	

Figure 4.2.-3. Proposed Consolidation Tests - 2/3

No.	Material	Plies N	Layup θ_N	Temp T, ^{o}F	Pressure P, PSI	Time @ T_{max} t, min	Special Test Feature	Comments
56	Cypac	16	UD	700	100	10		
57	7005			720				Cypac 7005
58				680				
59				700		5	Kapton Inserts	Evaluation
60						10	" "	
61						20	" "	
62			Preconsol			10	Ramp P	
63			UD				" "	
64			0/90				" "	
65			Quasi-iso				" "	-
66	PEEK		0/90	720	150	20		
67	Towpreg			700				PEEK Towpreg
68	Fabric			740				Fabric
69				720			Kapton Inserts	Evaluation
70							Ramp P	

Figure 4.2.-3. Proposed Consolidation Tests - 3/3

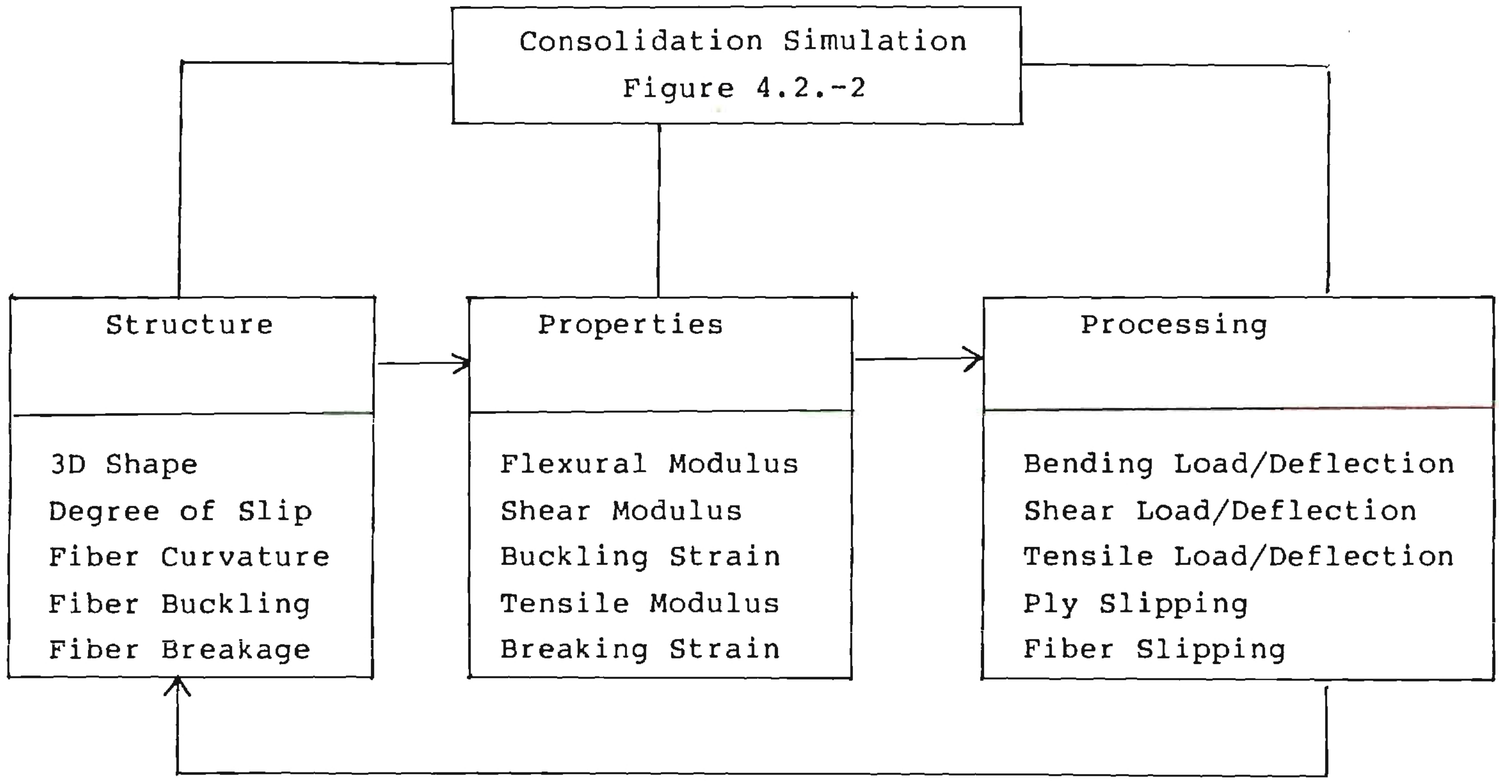

Figure 4.2.-4 Components of a Combined Consolidation/Forming Simulation

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 8

November, 1987

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:______________________

J.D. Muzzy

Project Director

December 3, 1987

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

November has been devoted to setting up and weaving towpreg fabric. The fabric structure is bidirectional with 400 denier carbon fiber binder yarn in the warp direction, similar to J.B. Martin Co structures. The fabric has 3 plies oriented $90/0/90^o$ with 0^o representing the warp direction. The initial structure attempted was balanced with 10 tows per inch in each direction and 2 binder yarns spaced every half inch in the warp direction. This structure was extremely difficult to weave because two binder yarns and one tow were in the same warp location. Consequently the binder yarns and towpreg would not seperate. This problem was eased by removing the towpreg from the same warp location as the two binder yarns.

The second structure attempted was also balanced, containing 8 tows per inch. This structure was found to be too flexible since it was difficult to maintain a consistent tow spacing in the weft direction.

The third and final structure being constructed has 8 tows per inch in each ply. Since there are two 90^o plies and one 0^o ply the three ply fabric is not balanced. The basis weight of this fabric is estimated to be 20.0 g/m^2.

The fabric is being prepared on a hand loom. For this reason the rate of fabric production is very slow. Automated weaving would be much faster.

2.2 Material and Process Modeling

Work is progressing on extending the viscosity model to lower temperatures to include the development of crystallinity and the glassy state.

The crystallinity model is being modified to include an increase in crystallinity due to lamellar perfection during annealing. This work is not in suitable form for reporting this month.

3.0 Problems

No significant problems were encountered this month.

4.0 Planned Activity

Most of December will be devoted to weaving. The model developments discussed in 2.2 will be continued.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 9

December, 1987

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:

J.D. Muzzy

Project Director

January 4, 1988

School of Chemical Engineering

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Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

The primary task of producing enough towpreg for weaving was accomplished. The processing conditions for this task are presented in Table 2.1-1 under run number 10-1. This tow is 5 mils thick and about 1/4 inch wide. The 3K tow splits into two primary plies. Each ply is substantially bonded even though tow spreading rollers were placed immediately after the oven in order to keep fibers separated. The driven pinch rolls contacted cold tow in order to prevent further consolidation. Consolidated tow is stiffer and therefore harder to wind. The tow passed over flexible foam brushes in order to remove loose hairs from the tow.Smaller quantities of sized tow were produced at the conditions presented in Table 2.1-1 under runs 10-2 and 10-3. The primary operating difference between these two runs is the elimination of tow spreading in run 10-3. Without tow spreading an essentially round tow is produced. This tow passed over a grooved teflon wheel to promote shaping and consolidation. Since the tow was not spread and the tow was partially consolidated, it was not necessary to brush off loose ends. The handling of these two sized tows in weaving is expected to be considerably different.

November and December has been devoted to setting up and weaving towpreg fabric. The fabric structure is bidirectional with 400 denier carbon fiber binder yarn in the warp direction, similar to J.B. Martin Co structures. The fabric has 3 plies oriented $90/0/90^{o}$ with 0^{o} representing the warp direction. The initial structure attempted was balanced with 10 tows per inch in each direction and 2 binder yarns spaced every half inch in the warp direction. This structure was extremely difficult to weave because two binder yarns and one tow were in the same warp location. Consequently the binder yarns and towpreg would not seperate. This problem was eased by removing the towpreg from the same warp location as the two binder yarns.

The second structure attempted was also balanced, containing 8 tows per inch. This structure was found to be too flexible since it was difficult to maintain a consistent tow spacing in the weft direction.

The third and final structure being constructed has 8 tows per inch in each ply. Since there are two 90^{o} plies and one 0^{o} ply the three ply fabric is not balanced. The basis weight of this fabric is estimated to be 300.0 g/m^2.

The fabric is being prepared on a hand loom. For this reason the rate of fabric production is very slow. Automated weaving would be much faster.

2.2 Material and Process Modeling

The focus in modeling has been on developing a correlation between resin viscosity and composite viscosity in undirectional drag flow. The composite viscosity is not a true viscosity because the imposed shear rate is not the resin shear rate. As a first approximation this relationship is

$$\dot{\gamma}_c = V_r \dot{\gamma}_r$$

where

$\dot{\gamma}_c$ = composite (sample) shear rate

V_r = volume fraction resin

$\dot{\gamma}_r$ = resin shear rate

In addition to this shear rate difference there is an additional resistance associated with the added surface area due to the presence of the fiber. This additional resistance to flow should be a geometric constant dependent on the direction of flow. In sum, an approximate relationship between shear stress and shear rate takes the form

$$\tau = g\eta\dot{\gamma}_c/V_r$$

where the new terms are:

τ = shear stress

g = geometric constant

η = resin viscosity

On this basis the unidirectional viscosity data obtained on the MER-1100A by the University of Akron is being analyzed. A preliminary evaluation indicates g is in the range of 10 and is smaller for flow perpendicular to the fiber axis.

The shear rates imposed by the MER-1100A are high for composites processing. The ability to collect viscosity data at lower shear rates will be discussed with the University of Akron.

Work is progressing on extending the viscosity model to lower temperatures to include the development of crystallinity and the glassy state.

The crystallinity model is being modified to include an increase in crystallinity due to lamellar perfection during annealing. The Georgia Division of LASC has developed a correlation between crystallinity and crystallization tempeature which represents experimental results well.

3.0 Problems

No significant problems were encountered this quarter.

4.0 Planned Activity

Phase II plans were updated last October. Our plans for the first quarter of 1988 follow.

4.1 Electrostatic Fluidized Bed Coating Process

Our primary emphasis will be on producing materials for characterization. The hand weaving of fabric will be completed as soon as possible. A portion of this fabric will be retained at Georgia Tech for characterization and the remainder delivered to LASC for process evaluation. Additional towpreg will be prepared for the next round of evaluation. This towpreg will be converted into fabric by automated weaving or braiding. During the first quarter of 1988 we intend to make final arrangements for the production of this fabric. We will conduct model validation experiments of electrostatic fluidized bed coating durign the first quarter after meeting sample production requirements.

4.2 Material and Process Modeling

We will focus on consolidation and forming model development. Thermal property models will be refined to include changes in value as a function of temperature and porosity. Refinements in elastic deformation during consolidation will be made provided apropriate experimental data is obtained. For mass transfer we focus on extending the temperature range of the viscosity model to low temperatures. A viscoelasticity model for Cypac 7005 will be developed provided appropriate rheological data is obtained. Since hydroforming will be emphasized during the first quarter, an analytical but elementary model of forming will be developed for comparison with the forming experiments. There is a critical need for experiments to validate and refine consolidation and forming models. A draft proposal from Georgia Tech has been submitted to AFWAL addressing this need.

Table 2.1-1

EFBC Processing Conditions
for October, 1987
(PEEK 150/3K AS 4)

Run Number	10-1	10-2	10-3
Fluidized Bed Length, Inches	18	18	18
Number of Tows	1	1	1
Tow Spreading	Yes	Yes	No
Tow Velocity, ft/min	10	17.8	17.8
Air Pressure, Psi	85	55	55
Air Flow, SCFH	13	10	10
Voltage, KV	80	50	50
Current, microamps	60	10	10
Oven Temperature, ^{o}C	500	550	550
Ave Powder Size, Microns	50*	50*	50*
Tow Resin Content, Vol %	40+	10*	10*
Tow Height, mils	5	5*	15
Tow width, mils	250+	250+	15
Amount Produced, grams	2090	219	129

*Estimated

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 10

January, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:

J.D. Muzzy

Project Director

February 8, 1988

School of Chemical Engineering

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Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

The hand weaving of towpreg has been stopped in order to check the quality of the fabric produced. A small sample was given to Matt Pursley for examination at the review meeting February 5th. The basis weight and thickness of the fabric are 370 g/m^2 and 0.75 mm. Thus, the bulk density of the fabric is 0.5 g/cm^3 which corresponds to a porosity of about 70%. The fabric is reasonably flexible. Georgia Tech has just obtained a Kawabata Evaluation System (KES) for measuring mechanical properties of fabrics (bending, tension, shear, compression and surface friction). We will check into quantifying the mechanical properties of the hand woven fabric with this instrument as soon as it is set up.

We have delivered small samples of towpreg to commercial weavers to assist them in ascertaining whether they can prepare fabric from the towpreg. The companies contacted to date are Atkins and Pearce, Brunswick technologies, Hexcel, J.B. Martin and Mutual Industries. In each case we have indicated the shape, resin content and extent of consolidation of the towpreg can be adjusted to some extent to suit their processes. We are looking for feedback this month.

2.2 Material and Process Modeling

We have reworked Dara and Loos' autohesion model (Report No. CCMS-85-10 and VPI-E-85-21 for NASA Langley) for general application to polymers other than polysulfone. They obtained the following correlation for polysulfone.

$$D_{AU} = 0.1953 \; (a_T \; t_{c\ ref})^{1/4} \tag{1}$$

where D_{AU} is the degree of autohesion, a_T is the WLF shift factor

$$\log a_T = \frac{-2.604 \; (T-210)}{47.682 + (T-210)} \tag{2}$$

and $t_{c\ ref}$ is the contact time in seconds at the reference temperature of 210°C. The contact time at other temperatures is obtained from

$$t_c = a_T \; t_{c\ ref} \tag{3}$$

Once D_{AU} reaches a value of 1.0, no further incease in adhesive strength can be achieved since the failure is entirely cohesive at this stage. Dara and Loos obtained the shift factor for polysulfone from viscosity measurements made at different temperatures and frequencies using the relationship.

$$\eta = a_T \eta_{ref} \tag{4}$$

where the reference viscosity at 210°C and zero shear rate is approximately 30 MPa·s. Eliminating a_T from equations (3) and (4),

$$t_c = \left(\frac{t_c}{\eta}\right)_{ref} \eta \tag{5}$$

Since $t_{c\ ref}$ equals 687 s for $D_{AU} = 1$,

$$t_c = 22.9\ \eta \tag{6}$$

when η is expressed in MPa·s. Thus, the contact time necessary to reach the cohesive strength of the matrix should be directly proportional to the viscosity of the polymer.

Based on equation (6), the required contact times to achieve good adhesion for many polymers at normal processing temperatures is quite short. Typically, the melt viscosity at these temperatures will be less than 1 kPa·s (10^4 Poise), which corresponds to a contact time less than 1 second.

The viscosity of PEEK 150 is below 10^4 Poise; hence, autohesion should not be a critical concern for APC 2.

3.0 Problems

No significant problems were encountered this month.

4.0 Planned Activity

4.1 EFBC Process

We will characterize the mechanicsl properties and consolidation of the hand woven fabric. We will prepare consolidated towpreg samples for C-scanning and mechanical testing. We will develop recommendations and cost estimates for commercially weaving towpreg.

4.2 Material and Process Modeling

We will focus on an analytical, elementary model for forming APC 2 for possible application to APC 2. We will seek data for modeling Cypac 7005.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 11

February, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:

J.D. Muzzy

Project Director

March 3, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

J.B. Martin, Inc and Mutual Industries Inc have responded to our request for quotes on preparing fabric from towpreg. These quotes will be reviewed at LASC-California Division on March 7th to resolve plans for producing fabric. Mutual Industries will prepare a 5H satin fabric whereas J.B. Martin recommends an unidirectional fabric.

J.B. Martin has prepared a 6"x20" sample of a "Double Weft Unidirectional NSC" fabric from our 40 volume % PEEK towpreg. Based on this trial run Philippe Combier of J.B. Martin has recommended changes in the characteristics of the towpreg to facilitate weaving. The primary difficulties encountered are stiffness of the tow and the tendency of the tow to split into two plies. The splitting created the most difficulty. We will focus on reducing this splitting even though the tow may be stiffer.

2.2 Material and Process Modeling

Since flexible plies with incomplete fiber wetting or incomplete consolidation within plies are being used during Phase II, we have developed a melt migration model for intraply consolidation. An interply consolidation model has been incorporated in the process simulation. The basis for the intraply consolidation model follows.

We assume the melt must permeate the fiber network normal to the fiber axis under an applied pressure gradient from resin rich to resin difficient spaces. An element depicting this flow problem is shown in Figure 1. This problem is analogous to permeation into a bleeder ply. The rate of penetration is given by

$$\frac{dZ}{dt} = \frac{-S}{\eta}\frac{dP}{dZ} \tag{1}$$

where S is the apparent permeability, η is the viscosity and dP/dZ is the pressure gradient. Based on the Kozeny-Carmen relationship, S is

$$S = \frac{r_f^2}{4k_z}\frac{(1-V_f)^3}{V_f^2} \tag{2}$$

where r_f is the fiber radius, V_f is the fiber volume fraction and k_z is the Kozeny constant for flow normal to the fiber axis. Based on Gutowski's studies, k_z should be 18 for well aligned fibers. Equation 1 can be integrated assuming dP, η and S are constant to obtain the time required for the resin to flow a penetration distance, Z. The integrated equation is

$$t = \frac{-\eta Z^2}{2S\Delta P} \tag{3}$$

If the parameters in equation 1 change with time, equation 1 can be integrated numerically or equation 3 can be summed for small increments of t or Z.

Following is an example. Assume the following properties representing dry fiber penetration:

V_f = 0.8

r_f = 3.5 microns

$-\Delta P$ = 100 psi

η = 3,500 Poise

Z = 70 microns (10 fibers)

The time obtained is about 10 minutes. This example corresponds to PEEK/AS 4 fiber at 720°F. The time is a reasonable estimate of the additional time required to partly or fully wet out comingled tow in a laminate.

3.0 Problems

No significant problems were encountered this month.

4.0 Planned Activity

4.1 EFBC Process

We will characterize the mechanical properties and consolidation of the hand woven and J.B. Martin fabric. We will prepare consolidated towpreg samples for C-scanning and mechanical testing.

4.2 Material and Process Modeling

We will focus on an analytical, elementary model for forming APC 2 for possible application to APC 2. We will seek data for modeling Cypac 7005.

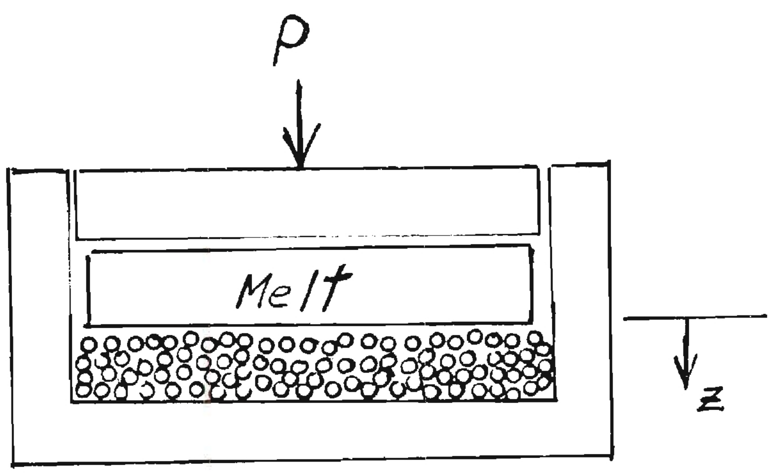


Figure 1. Model for Melt Penetration of Fibers

LIBRARY DOES NOT HAVE

MONTHLY TECHNICAL REPORT for MARCH 1988

F18-6A

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 13

April, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:______________________

J.D. Muzzy

Project Director

May 10, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

We have been working on producing towpreg for J.B. Martin to weave. The problem of towpreg splitting into two plies has been greatly reduced, which should facilitate weaving. We plan to produce 12 pounds of towpreg containing 40 volume % PEEK and 60 volume % 3K AS4. We are only running one towpreg through the bed since we don't have sufficient apparatus to maintain independent tension control on multiple tows. Consequently, our production rate is in the range of 0.1 to 0.2 lb/hr. We expect to have 12 lbs of towpreg available for J.B. Martin by mid June.

2.2 Material and Process Modeling

We are focusing on process model refinements. At this time these refinements are coming from Larry Norpoth's thesis work on consolidation. His data has not been converted into a form appropriate for reporting this month.

We have initiated forming studies of quasi-isotropic APC 2 in an independent research program. Forming loads are substantially lower than the applied loads necessary to reconsolidate the laminates. Also, consolidation times are greater than forming times. Thus, consolidation appears to be the rate controlling feature in forming.

We have not received any new material data so we have not expanded our models of materials.

3.0 Problems

No significant problems were encountered.

4.0 Planned Activities

Our work in May will be a continuation of our activities in April. The production of 12 lbs of towpreg will comprise our major effort well into June.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 14

May, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by: ______________________

J.D. Muzzy

Project Director

June 10, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating proess for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 ELectrostatic Fluidized Bed Coating (EFBC)

We have been producing towpreg for J.B. Martin to weave. The problem of twopreg splitting into two plies has been greatly reduced, which should facilitate weaving. As of today we have produced 5 pounds of towpreg containing 40 volume percent PEEK and 60 volume percent 3K AS-4. We expect to deliver 12 lbs of towpreg to J.B Martin by June.

2.2 Material and Process Modeling

We are focusing on process model refinements. At this time these refinements are coming from Larry Norpoth's thesis work on consolidation. His data has not been converted into a form appropriate for reporting this month.

Our design group was assigned the task of determining a scale-up design and its economic feasibility for the existing thermoplastic powder prepregging processing. The modified electrostatic fluidized bed coating process is shown in Figure 1. The economic feasibility for this modified process is being studied.

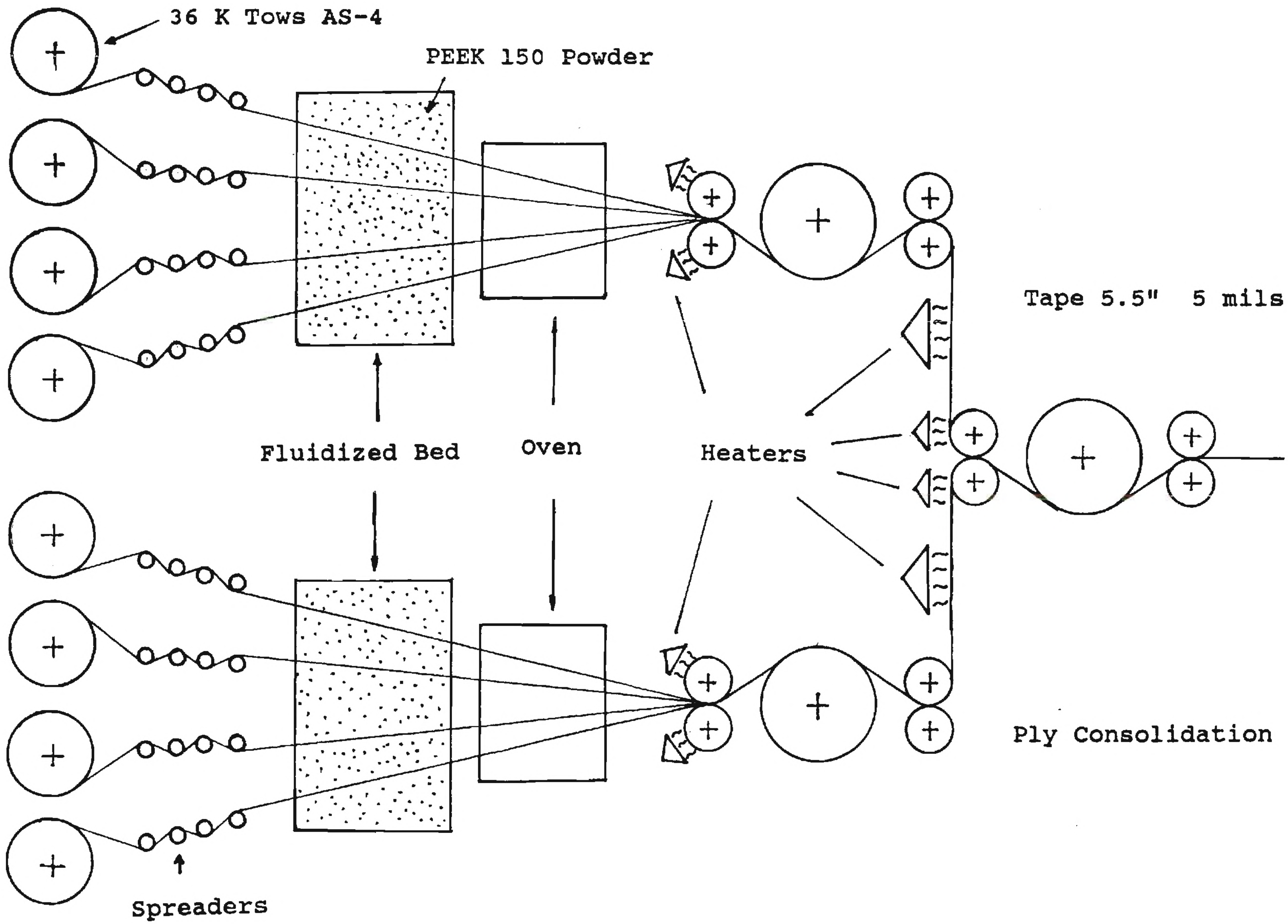
3.0 Problems

No significant problems were encountered.

4.0 Planned Activities

Completion of the production of 12 lbs of towpreg and delivery to J.B. Martin will comprise our major effort in June.

Tow to Tape Design



MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 15

June, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:

J.D. Muzzy

Project Director

July 10, 1988

School of Chemical Engineering

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1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the devleopment of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

The production of towpreg for J.B. Martin has been completed. The towpreg will be delivered early in July to J.B. Martin.

A systematic exploration of EFBC processing variables has been initiated. This work is being performed by Vivan Thammongkol for her M.S. thesis at no cost to the program. Vivan has conducted screen analysis of as received PEEK, PEEK remaining in the bed and PEEK subjected to Wiley milling. In each case the average particle size is well over 100 microns. The effect of using coarse particles is to reduce the line speed. However, towpreg containing 40 volume % PEEK can still be produced. Increasing the bed voltage and air flow both increase resin pickup whereas increasing line speed reduces resin pickup. Oven temperatures between 380 and 600^{o}C does not effect the resin retained on the fiber. These samples will be examined for possible degradation and changes in wetting.

An undergraduate design group has completed a study of converting dry carbon fiber tow and PEEK powder into tape by the

EFBC process coupled with roll consolidation. Tape was selected as a product form because it is well defined with an established sales price. Ultimately we hope to compare the cost of tape production with fabric production. The tow to tape design is illustrated in Figure 1. There are 8 creels of 36K AS4 tow feeding the process. Each tow is spread to a width of 5 ½ inches, corresponding to the final tape width. The tows pass through two EFBC units spread vertically. (Figure 1 is essentially a shcematic view looking down on the process). The EFBC units are the same size as the larger bed in our lab. Radiant ovens are used to melt the PEEK on the tows. Radiant heaters are used after the ovens to keep tapes and surface temperatures of the rolls hot. The final tape size corresponds to commercial APC2 tape sold by ICI.

Table 1 summarizes some of the economic estimates for this process. The product costs are given in more detail in Table 2 since different estimators may want to use different factors. Based on these estimates the proposed process should be highly profitable. The primary processing features which would reduce costs further are increasing the processing rate and reducing scrap. Higher processing rates can be achieved by redesigning the EFBC bed and oven. Less scrap depends on using longer lengths of tow since replacing a creel requires stopping the process. It is also necessary to establish that 5 ½ wide tows can be uniformly coated.

2.2 Material and Process Modeling

During June, Larry Norpoth completed his experimental work for his thesis on APC2 consolidation. He has studied the effects of pressure, temperature, number of plies and layup sequence on consolidation parameters. For unidirectional layups he obtained reasonably constant values for the consolidation and flow coefficients, C and K respectively. Excluding high and low values the average values and ranges obtained are:

$$C = 0.09 + 0.03/-0.04$$

$$K = 0.30 + 0.12/-0.08$$

In quasi-isotropic and transverse layups squeeze flow of resin and fiber normal to the fiber axis dominates. This flow process will be analyzed in more detail in the near future.

3.0 Problems

No significant problems.

4.0 Planned Activities

During July weaving and characterization of towpreg will be emphasized. Further analysis of transverse flow during consolidation will be done since this is important in forming and consolidating multi-axial composites.

Table 1

Economic Evaluation of the Tow to Tape Process

Design Basis	
Tape Produced	50,000 lb/yr
. 60 volume % AS4	
. 40 volume % PEEK 150	
Scrap Produced	7,500 lb/yr
Production Rate	9 ft/min
Cost of AS 4	$28/lb
Cost of PEEK 150	$26.50/lb
Average powder size	100 microns
Investment Costs	
Purchased Equipment	$160,000
Fixed Capital	650,000
Working Capital	170,000
Total Capital	820,000
Product Costs	$/lb
Raw Material	31.50
Direct Production	38.00
Manufacturing	44.00
General Expenses	16.00
Total Product	60.00
Profitability	
Sales Price	180.00
Product Cost	60.00
Gross Income	120.00

Table 2

Tow to Tape Process
50,000 lb/yr Production

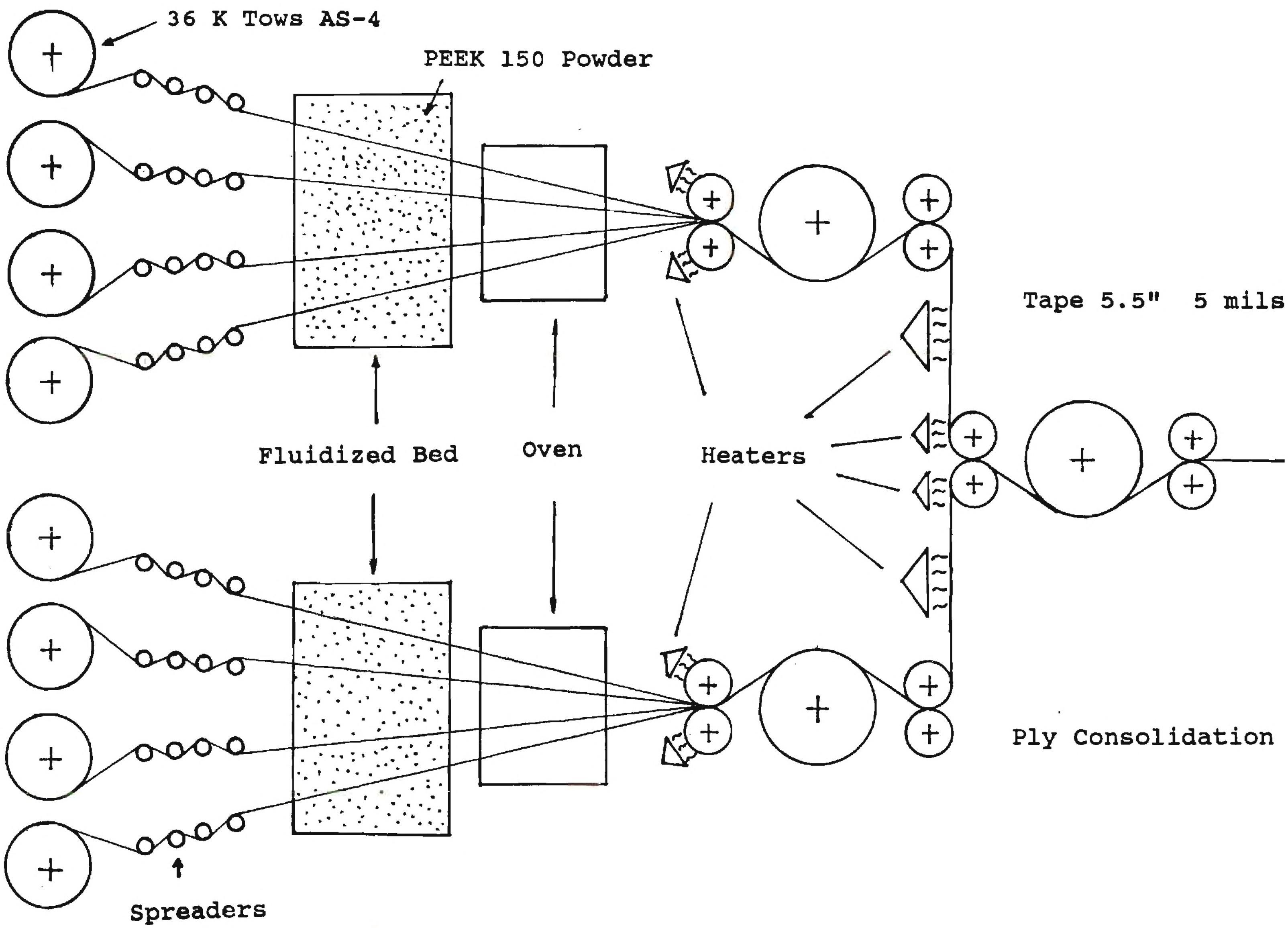
	1,000 $/yr	$/lb
I. Manufacturing Cost		
A. Direct Production Cost		
1. Raw Materials a. PEEK $26.50/lb x 19,000 lb/yr = $503,500 b. Carbon Fiber $28.00/lb x 38,500 lb/yr = $1,078,000	$1,582	31.64
2. Operating labor 2 operators x $10/lb x 8,000 hrs/yr	160	3.20
3. Supervision and Clerical 15% of A 2	24	0.48
4. Utilities 20 KW x 8,000 hrs/yr x $0.10/KWH	16	0.32
5. Maintenance and repairs 10% of fixed capital ($650,000)	65	1.30
6. Operating supplies 20% of A 5	13	0.26
7. Lab charges 20% of A 2	32	0.64
8. Patents and royalties $0.10/lb	5	0.10
Direct Production Cost Total	1,897	37.94

Table 2 (cont'd)

Tow to Tape Process
50,000 lb/yr Production

	1,000 $/yr.	$/lb
I. Manufacturing Cost (cont'd)		
B. Fixed Charges		
1. Depreciation 10% of fixed capital	65	1.30
2. Local taxes 2% of fixed capital	13	0.26
3. Insurance 2% of fixed capital	13	0.26
Fixed Charges Total	91	1.82
C. Plant Overhead 80% of A2, 3 and 5	200	4.00
Manufacturing Cost Total	2,188	43.76
II. General Expenses		
A. Administrative 50% fo A2, 3 and 5	125	2.50
B. Selling Costs $10/lb 500	500	10.00
C. R and D Costs $2/lb	100	2.00
D. Financing 3% of total capital	25	0.50
Total General Expenses	750	15.00
Total Product Cost	2,938	58.76
Rounded Off	3,000	60.00

Tow to Tape Design



MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C-5008

Monthly Technical Report No. 16

July, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:

J.D. Muzzy

Project Director

August 16, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1.0 Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the devleopment of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

J.B. Martin has been converting the PEEK/carbon fiber towpreg into unidirectional fabric. Delivery of the fabric is expected mid-August.

Characterization of EFBC processing parameters continued during July. The results will be reported when the study is completed.

A videotape of the EFBC process was prepared.

2. Material and Process Modeling

Careful measurements of resin and total pressure have been made during consolidation of APC-2 at 381^{o}C and 100 psi. As illustrated in Figure 1, there is a substantial fiber network pressure during consolidation. Since APC-2 plies contain 61 volume % fiber initially, a much lower network pressure was anticipated. These results will be checked further since the high fiber network pressure will require adjusting the value of the flow coefficient, K.

3.0 Problems

No significant problems.

4.0 Planned Activities

During August further characterization of towpreg is planned. As soon as fabric is obtained from J.B. Martin, it will be consolidated and checked for voids. Additional characterization of consolidation is planned.

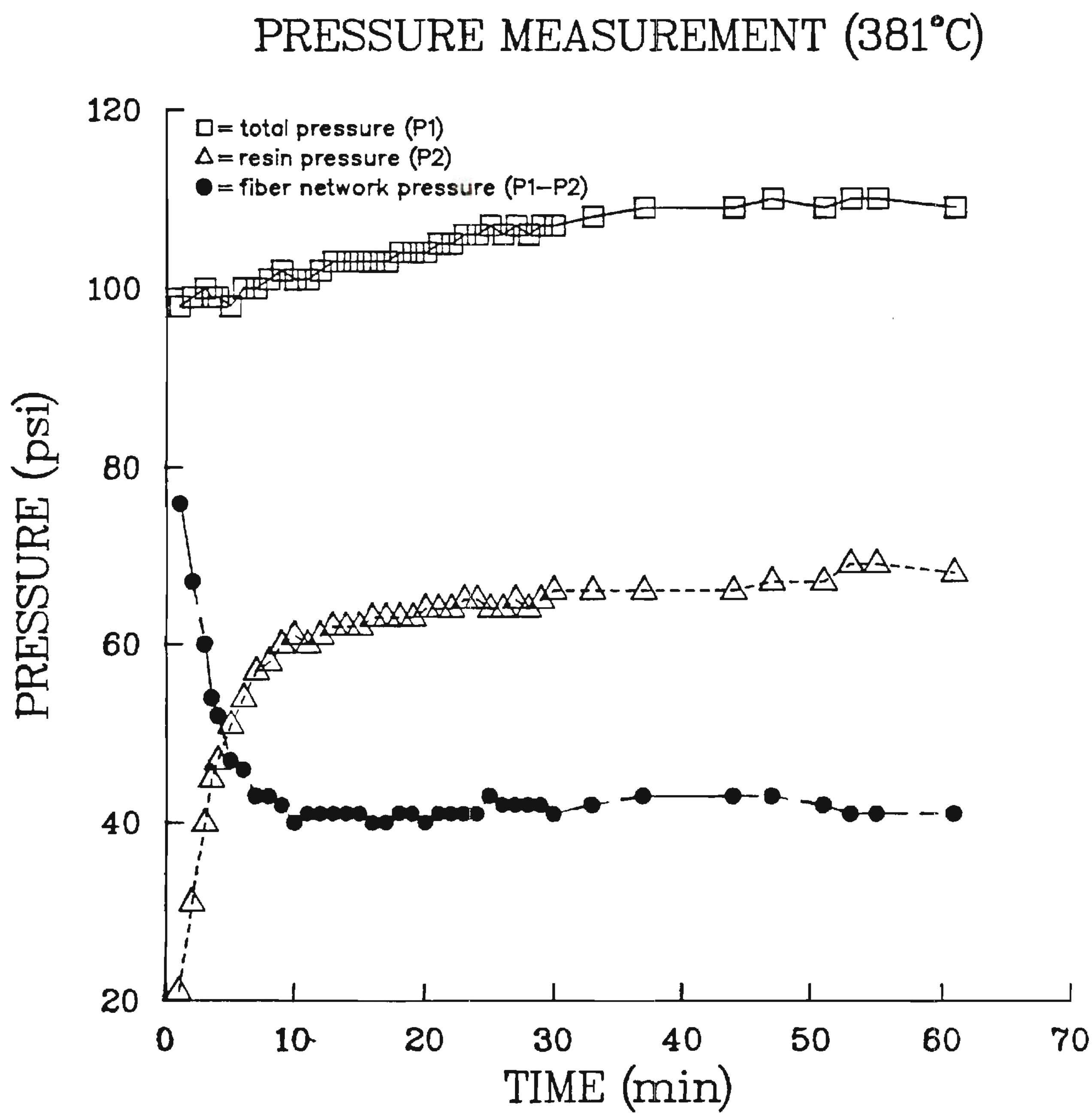


Figure 1. Pressure Measurements during consolidation of 24 plies of unidirectional APC 2 tape at 381°C and 100 psi.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C 5008

Monthly Technical Report No. 17

August, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:

J. D. Muzzy

Project Director

September 8, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1. Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

The weft fabric of PEEK/carbon fiber towpreg arrived September 2nd. The fabric is 39.4 inches wide and 12 yards long. The binder filament is 5 mil PEEK. The basis weight is 8.1 oz/sq. yd. The total weight of fabric is 7.2 lbs. Due to difficulties in taking off the towpreg from the bobbins, it was not possible to produce 10 lbs of fabric. The payoff system which does not create twist in the towpreg could not be used since it only operates at high speed. Due to the use of non-standard bobbins and irregular winding the towpreg would frequently break. Therefore, many of the bobbins were unwound and others were let off from the end of the bobbin, which introduces twist. Visual inspection of the fabric does show spots with twist as well as spots with frayed towpreg. However, the defects are less than 5% of the fabric area. Photographs of the fabric have been taken and characterization of the fabric will begin this month.

The PEEK on the towpreg does not degrade when the oven is set at 650°C. This stability was determined by comparing crystallization and melting responses of PEEK 150 with towpreg exposed to 350 through 650°C oven temperatures. The stability is attributed to the short residence time of 10 seconds in the oven. These samples will be examined by SEM to determine whether improved fiber wetting is achieved at higher oven temperatures.

Tests have been inititated to determine whether the size distribution of the powder deposited on the tow is similar to the powder size distribution in the bed. Preliminary results indicate that the average powder size is the same on the tow and in the bed. However, this conclusion is based on comparing particle sizes by seive analysis for the bed with quantitaitve photomicroscopy analysis of the powder from the towpreg. This month the powder from the bed will be analyzed by microscopy. If it is confirmed that there is no significant difference, then the long term operation of an EFBC line will be easier to maintain.

Five samples of towpreg have been consolidated in a press at the following conditions:

layup:	unidirectional
size:	4 x 1.6 x 0.16 inches
pressure:	440 psig
temperature:	720°F
hold time:	20 minutes at max. temp.
cooling:	slow and under max. pressure

No squeeze out of resin was apparent. The surfaces indicate significant misalignment of tows. After cutting the samples to approximately 3 inches in length, the C-scans shown in Figure 1 were obtained with the loss set of 8dB. The bottom sample appears to be free of porosity. These samples will be subjected to flexural testing this month.

2.2 Material and Process Modeling

Inconsistent results for network pressure have been obtained in consolidating APC 2 plies at 381^{o}C and 100 psi. These tests will be repeated and refined until consistent results are obtained.

Meetings were held with Matt Pursley regarding possible changes in thermal conductivity during consolidation. The possibility of measuring thermal conductivity at Georgia Tech is being explored.

3.0 Problems

No significant problems.

4.0 Planned Activities

During September, consolidation and mechanical testing of towpreg fabric will be emphasized. Further characterization of the EFBC operation is planned. Electrostatic Technology, Inc. will be visited September 13th regarding techniques for improving towpreg. Additional characterization for process modeling is planned.

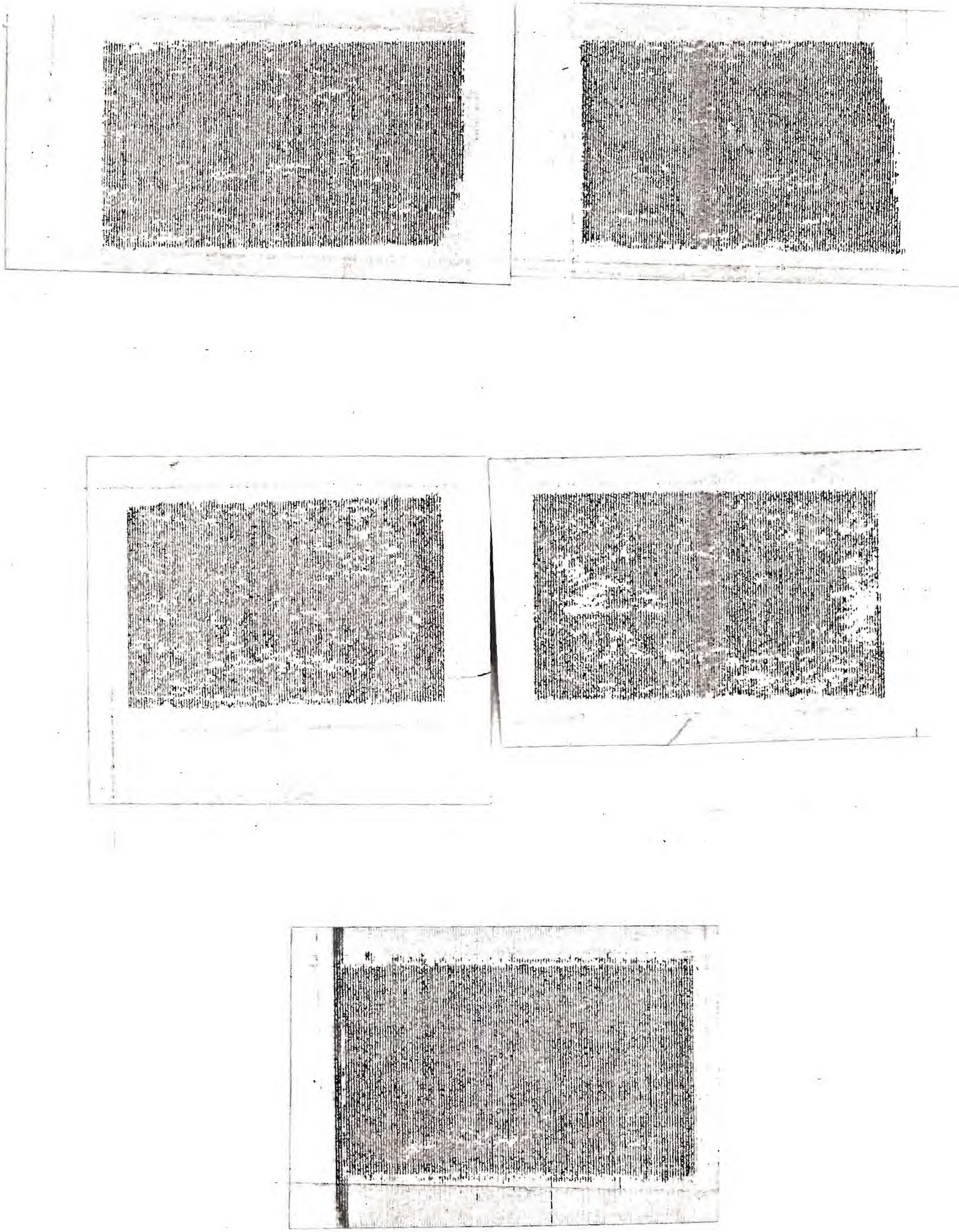


Figure 1. Ultrasonic C-scans from five consolidated towpreg samples with the loss set at 8dB

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C 5008

Monthly Technical Report No. 18

September, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by:

J. D. Muzzy

Project Director

December 21, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

Due to a reduced level of activity on this project a report on progress has been deferred until report number 21.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C 5008

Monthly Technical Report No. 19

October, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by: D. Muzzy

Project Director

December 21, 1988

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Georgia Institute of Technology

Atlanta, Georgia 30332-0100

:

Due to a reduced level of activity on this project a report on progress has been deferred until report number 21.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C 5008

Montly Technical Reprot No. 20

November, 1988

Prepared for

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Marietta, Georgia

Prepared by: J. D. Muzzy

Project Director

December 21, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

Due to a reduced level of activity on this project a report on progress has been deferred until report number 21.

MANUFACTURING SCIENCE OF COMPLEX SHAPE THERMOPLASTICS

Contract No. 01-87-185

AF Contract No. F33615-86-C 5008

Monthly Technical Report No. 21

December, 1988

Prepared for

Lockheed Aeronautical Systems Co - Georgia Division

Marietta, Georgia

Prepared by: J. D. Muzzy

Project Director

December 21, 1988

School of Chemical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0100

1. Introduction

There are two major projects for Georgia Tech: (1) the development of an electrostatic fluidized bed coating process for producing flexible thermoplastic prepreg and (2) the development of material and process models for thermoplastic composite processing.

2.0 Program Status

2.1 Electrostatic Fluidized Bed Coating (EFBC)

During the Fall Quarter Vivan Thammongkol finished a draft of her thesis on EFB coating of PEEK 150 powder on Hercules unsized, AS-4, 3K, carbon fiber tow. Some of her results will be reviewed here. The thesis should be completed in March.

Three average powder sizes have been studied: 90, 110 and 240 microns. All three powders have a fairly broad distribution in powder size. The 90 micron powder was purchased directly from ICI. The 110 micron powder was prepared from coarse powder, about 400 microns, by grinding using a Wiley mill. The 240 micron powder was prepared by air milling the coarse powder at Garlock, Inc. The powder prepared by Garlock was used to produce the towpreg for the fabric samples since over 20 pounds was available.

Table 1 illustrates the potential for selective deposition on the tow. The oven was turned off during these experiments in order to recover the powder deposited on the tow. The recovered powder size was determined by quantitative analysis of optical micrographs, which provides average particle sizes close to the values obtained by seive analysis. Although a low air flow rate in the fluidized bed promotes the deposition of finer powder, a high air flow rate leads to the deposition of powder equivalent to the size of the powder in the fluidized bed.

Tow spreading improves the degree of mixing between the powder and tow. Figure 1 shows the effect of the number of rollers on the degree of spreading. Figure 2 demonstrates that more spreading increases the flexibility of the tow. Increased tow flexibility will lead to more flexible fabric prepregs. Unfortunately adding more rollers leads to tow separating into two plies rather than more spreading. This separation is characteristic of the Hercules AS4 tow on hand. Hercules now produces a tow which won't separate into two plies. We are ordering this tow for evaluation.

Spreading using rollers can break fibers due to friction and requires relatively high line tension. Therefore we have been building and testing pneumatic or venturi type air spreaders. We have found this type of spreader can easily spread the 3K tow more than one inch wide-enough to see daylight between each fiber. At this time we cannot obtain consistent spreading so we have not been able to make towpreg. We have identified the system design modifications which should enable us to spread tow consistently and continuously.

Using tow spread with nine rollers, Vivan Thamongkol has studied a number of key processing parameters. Some of these results are presented in Figures 3 through 5. The pickup of powder is increased if the air flow and voltage are increased and if the powder size and tow velocity are decreased. More spreading also increases powder pickup. We intend to focus on obtaining finer powder as well as increasing spreading since both parameters increase degree of mixing, flexibility and rate of processing.

2.2 Material and Process Modeling

Georgia Tech has been assisting Matt Pursley on an as needed basis this past quarter. No material data has been submitted for modeling. Since the focus of process modeling has been on thermal behavior, relevant information in this area has been sought.

Grove (1) has published a thermal model for tape laying APC2 using laser heating. The model predicts temperature histories as a function of angle of incidence of the laser, laser distance from the nip, laser power, lay up speed and laminate thickness. Measured heat capacities, thermal conductivities (axial and transverse) and surface reflectances versus temperature are incorporated in the model. Post-consolidation cooling is included in the model. Suitable thermal processing windows are defined; but, these windows have not been validated.

Upadhyay (2) has published a mold heating analysis and optimization scheme for compression molding composites. The paper focuses on integrally heated tooling and the placement of heating elements. Uniformity of surface temperature is optimized. The paper includes validation experiments. Cooling is not considered.

Muzzy, et. al. (3) have submitted a paper for publication on thermoforming APC2. This paper focuses on deformation processes in forming. Flexural surface strains as a function of temperature and applied load are reported for a single ply of APC2- See Figure 6. The ply exhibits a purely elastic response above 340°C - see Figure 7. The ease of inducing transverse flow during forming or consolidation is illustrated in Figure 8. For pure transverse flow at 382°C an apparent viscosity of 0.1 (MPa)(s). was obtained for the fiber filled system - see Figure 9. This viscosity is about 200 times the zero shear rate viscosity for neat PEEK 150.

Copies of these three papers are enclosed.

3.0 Problems

No significant problems.

4.0 Planned Activities

Process modeling of the EFBC process and forming will continue as thesis research. New spreading systems and finer powder will be sought for the EFBC process. A presentation for the review meeting in February will be prepared.

5.0 References

1. Grove, S.M., "Thermal Modelling of Tape Laying with Continuous Carbon Fiber Reinforced Thermoplastic", Composites, 19, 5, 367-375 (1988).

2. Upadhyay, R.K., "Compression Molding of Composites: Mold Heating System Design," Adv. In Polymer Technology, 8, 3, 243-264 (1988).

3. Muzzy, J-D., X. Wu and J.S. Colton, "Thermoforming of High Performance Thermoplastic Composites", SPE ANTEC, submitted for publication (1988).

Table 1 Selectivity in Deposition

Processing conditions		
Powder size (microns)	110**	
Tow velocity (ft/min)	10.5	
Bed voltage (kV)	80	
Oven temperature	off	
Bed air flow rate (ft^3/min)	8	12.5
Deposition on Tow		
Powder size (microns)	74*	110*
Standard deviation	4.5*	7.5*

* By optical microscopy

** By screening

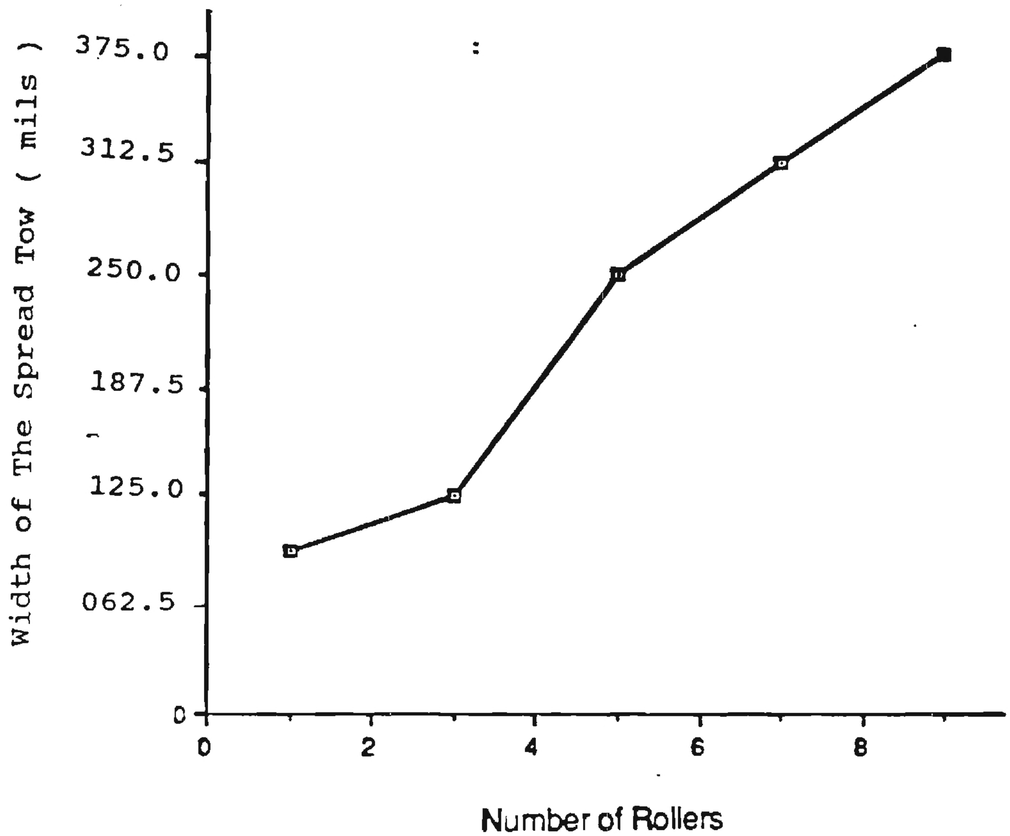

Figure 1 The Width of The Spread Tow as a Function of Number of Rollers Used in The Spreading System

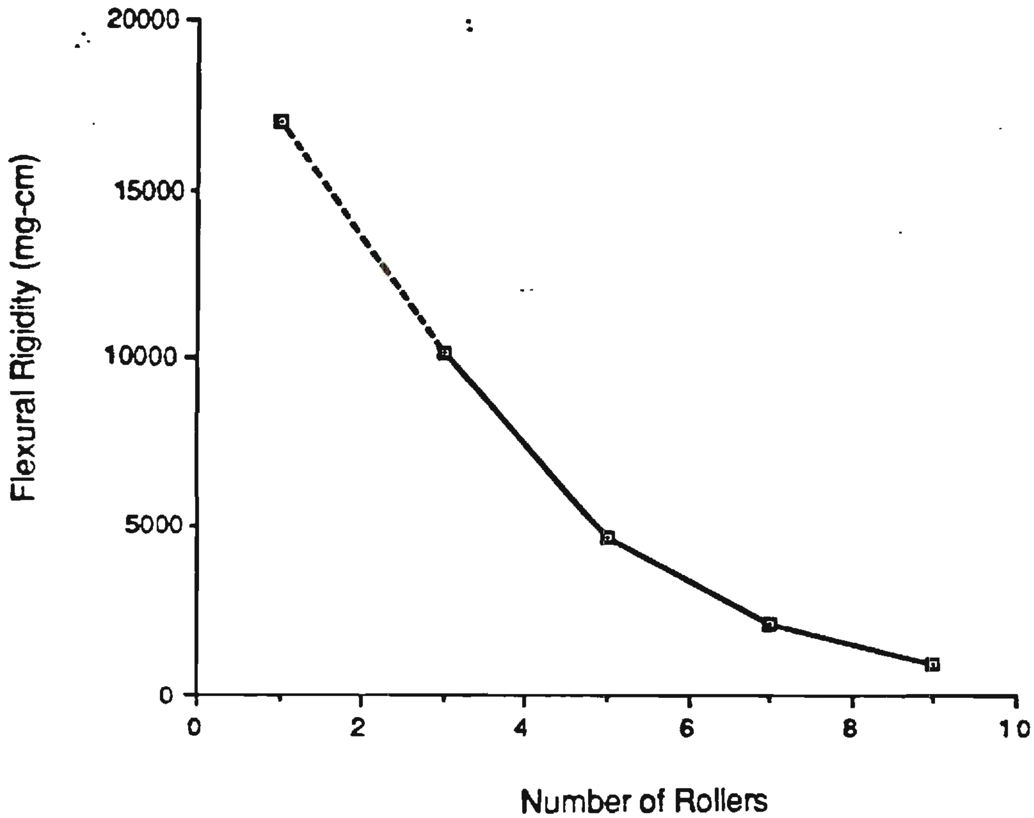

Figure 2 Effect of Tow Spreading on The Flexibility of The Towpreg

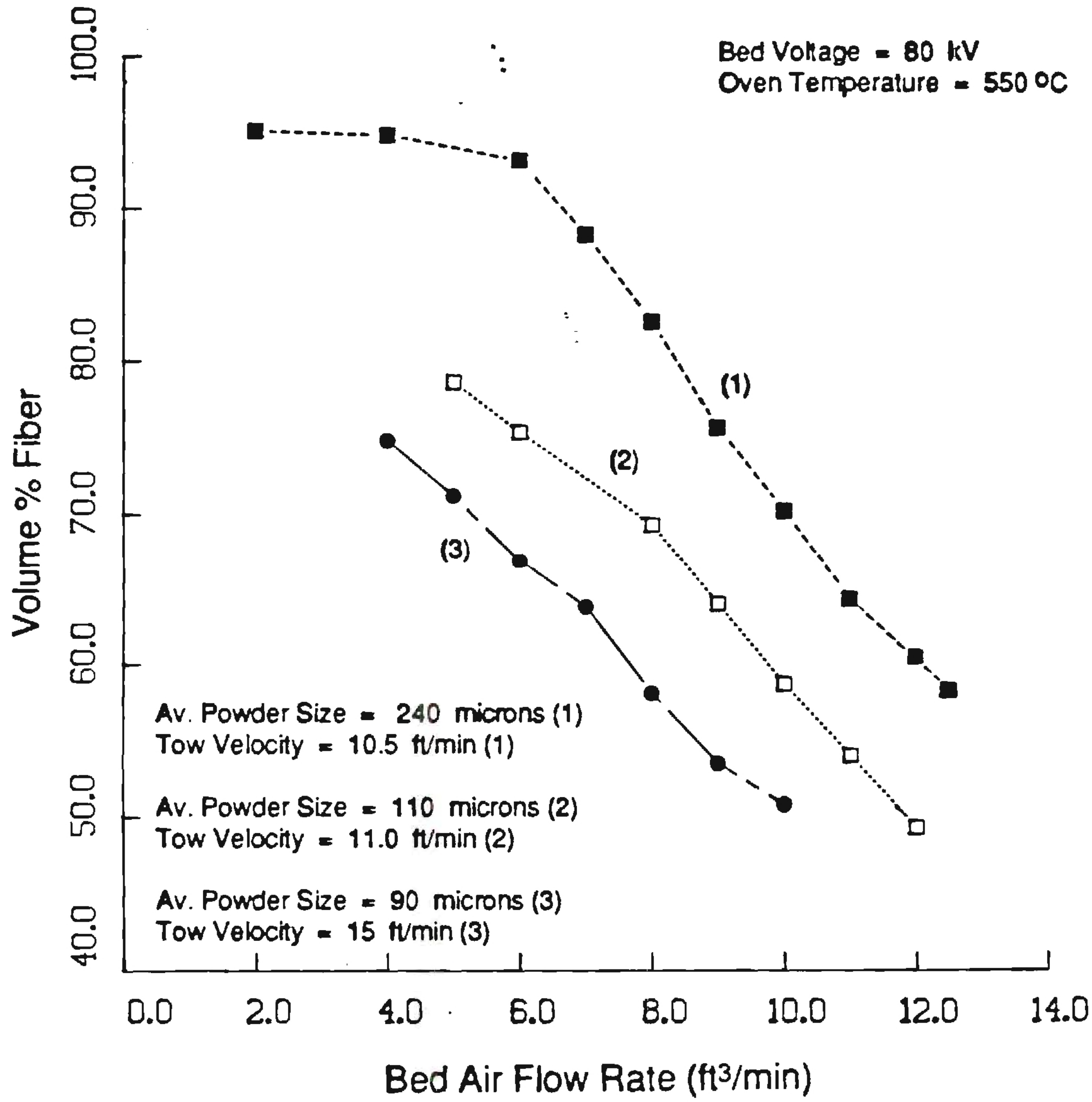

Figure 3 Effect of Bed Air Flow Rate on Volume% of Fiber

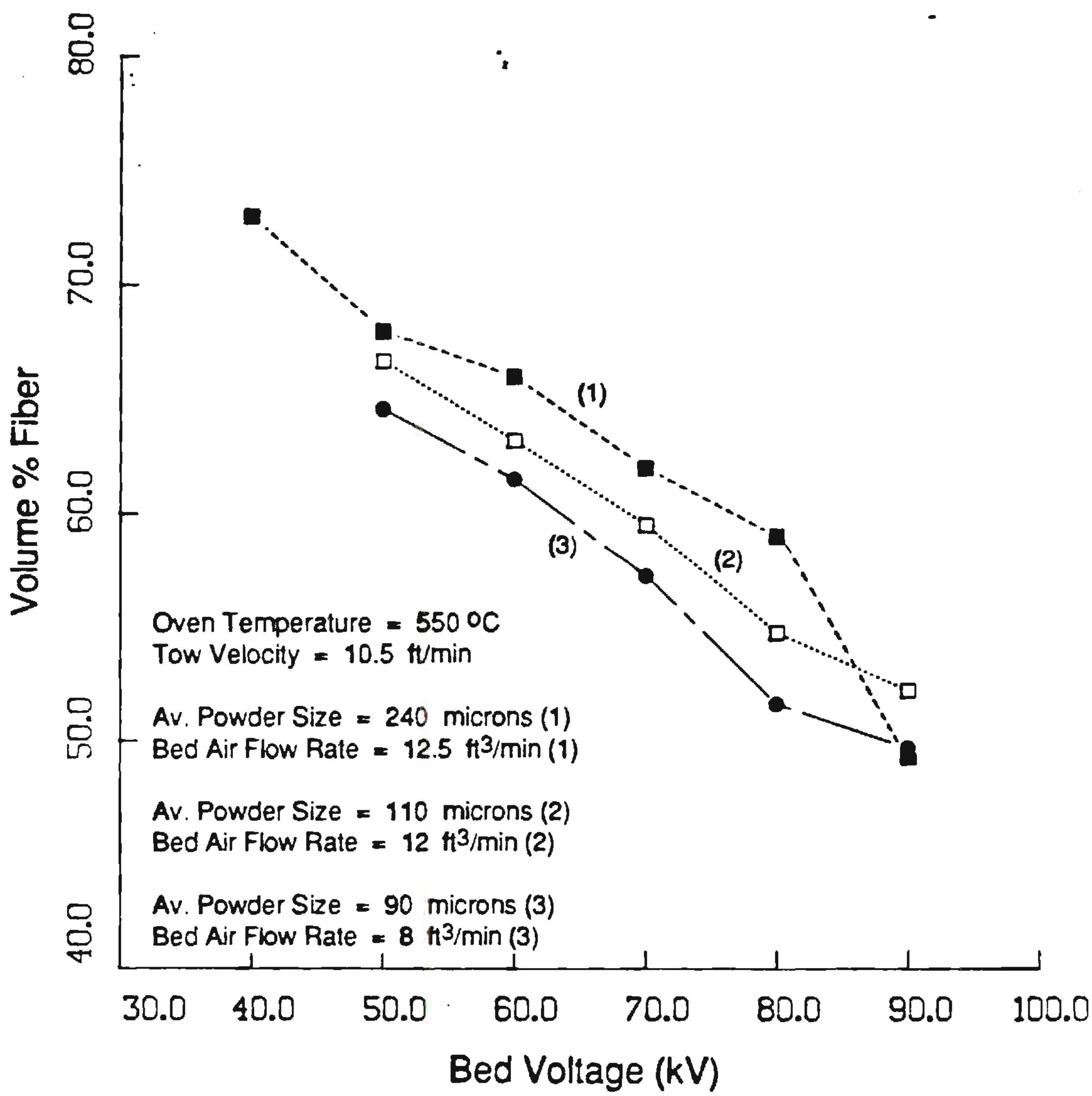

Figure 4 Effect of Bed Voltage on Volume% Fiber

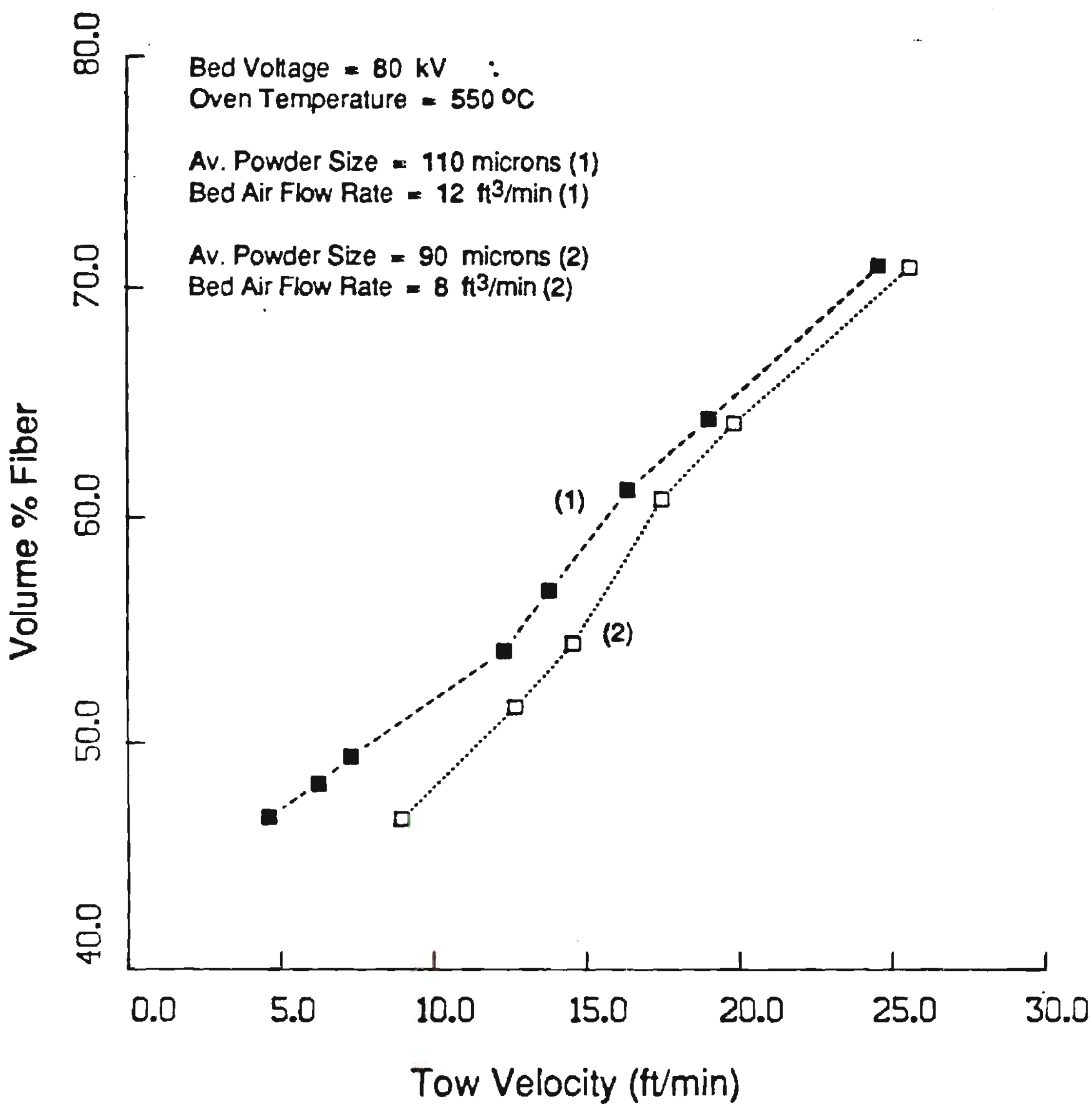

Figure 5 Effect of Tow Velocity on Volume% Fiber

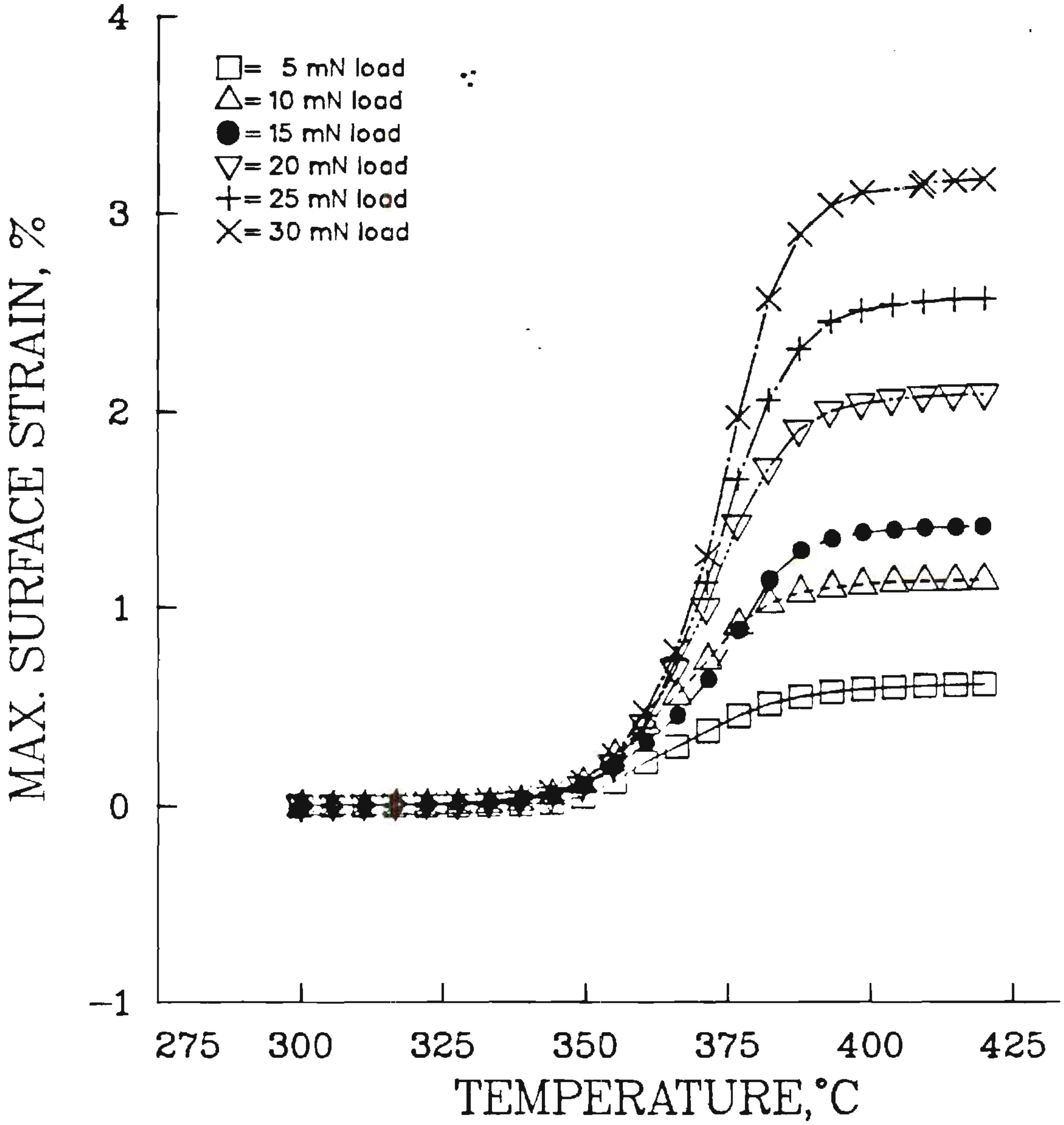

Figure 6 Flexural surface strain versus temperature for a single ply of APC-2 measured by TMA at a heating rate of 20 ^{0}C/min.

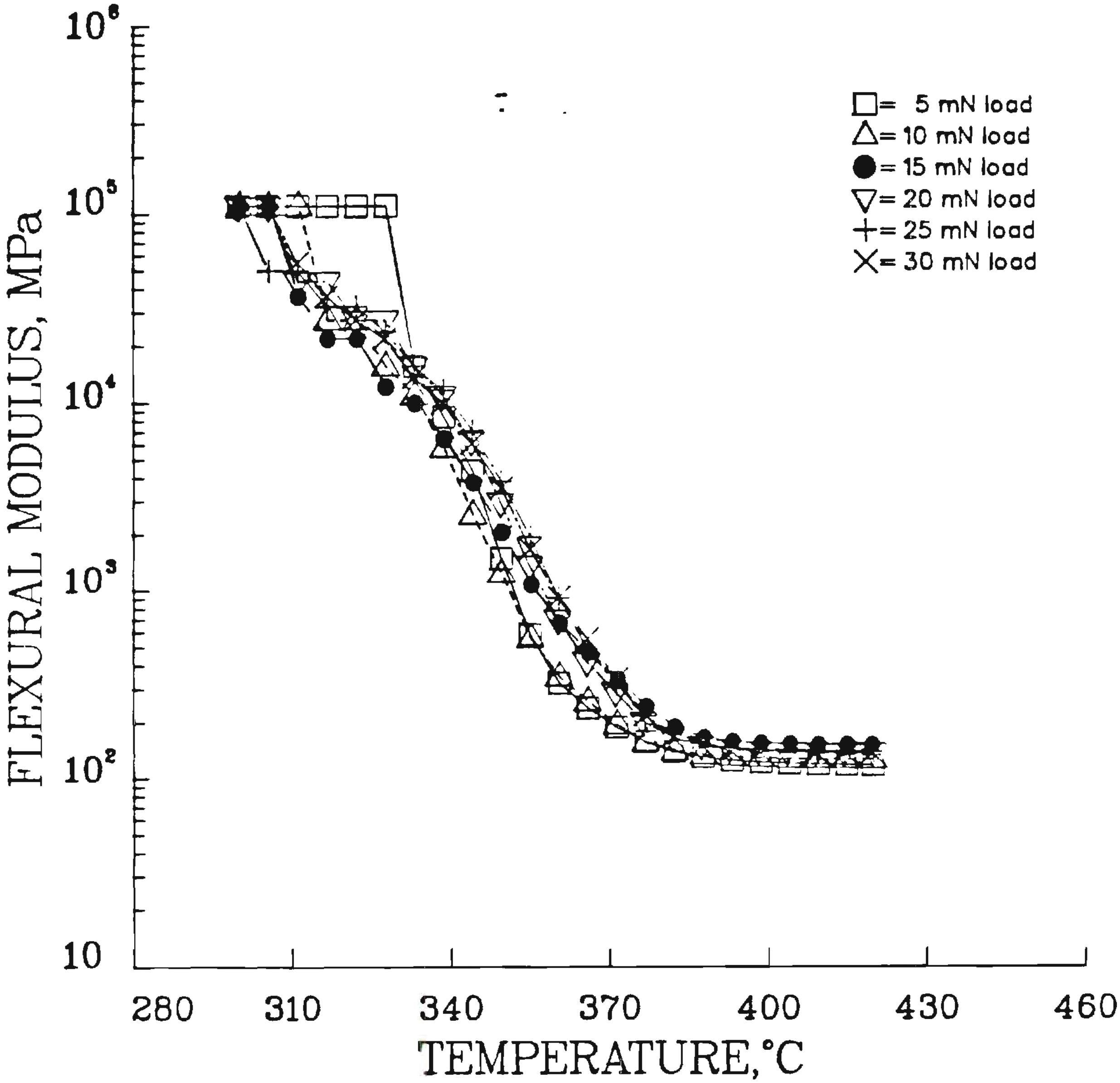

Figure 7 Flexural modulus versus temperature for a single ply of APC-2 based on data in Figure 4

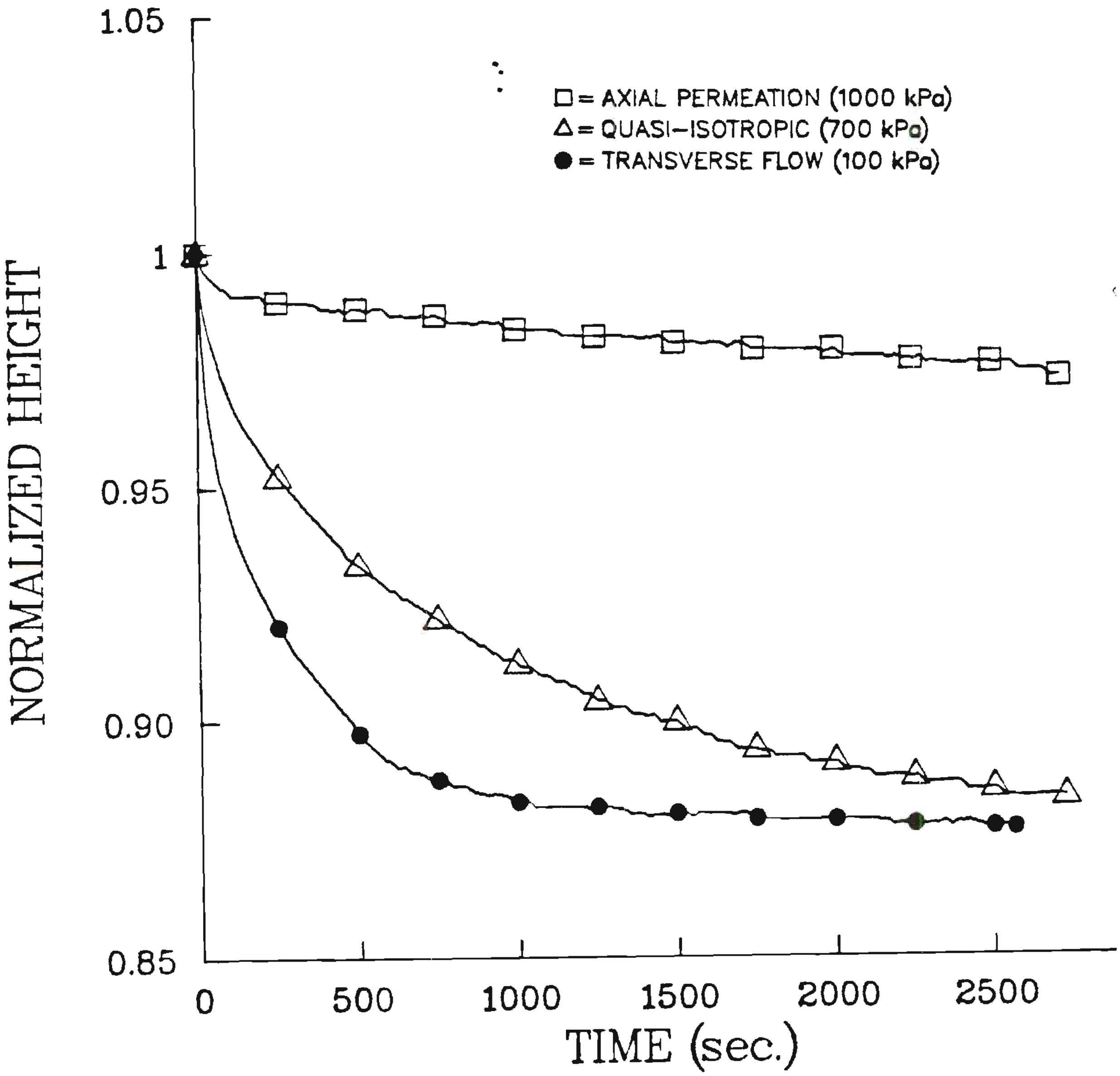

Figure 8 Comparison of one dimensional flow behavior of APC-2 tape layups at 382 °C

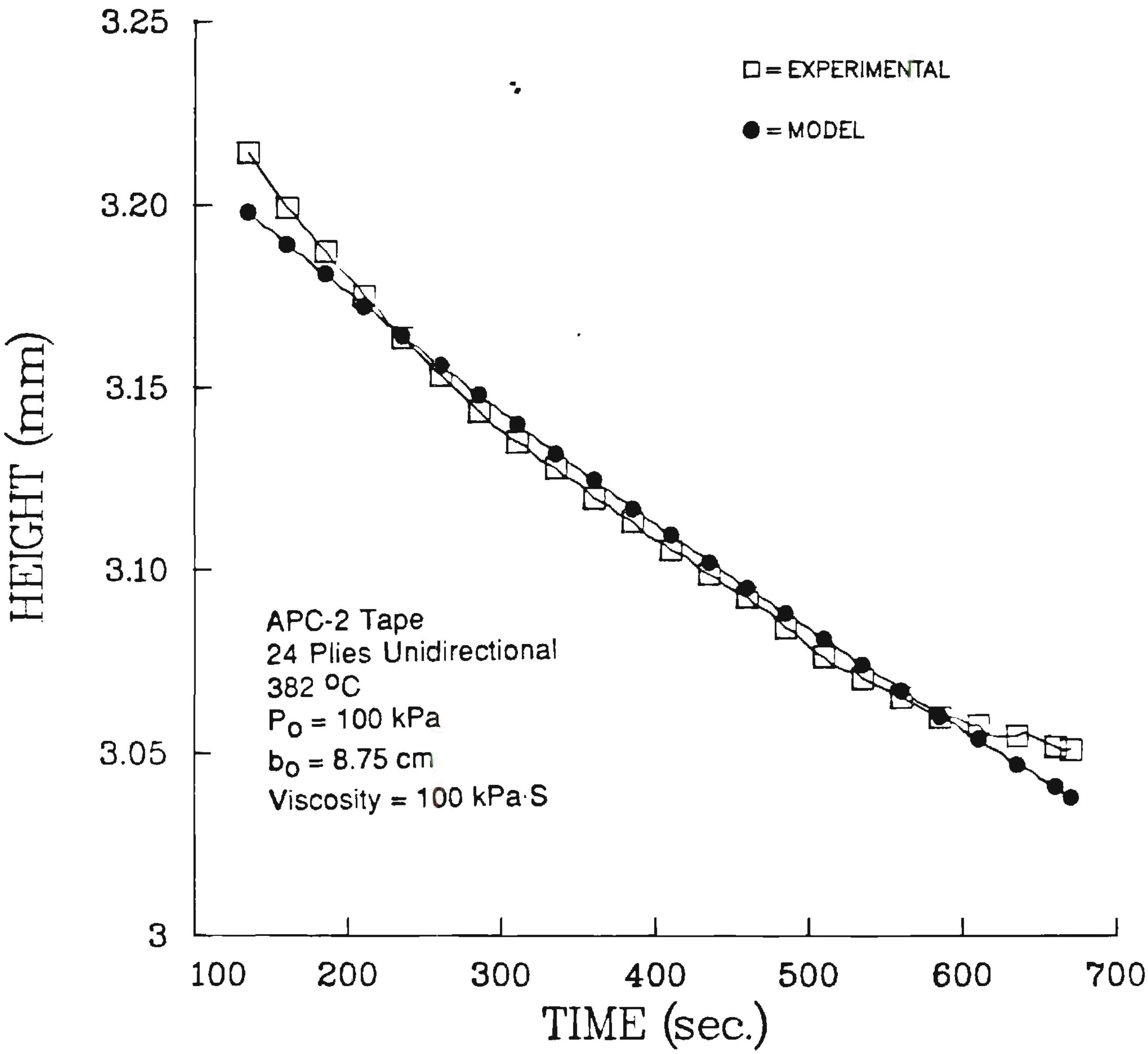

Figure 9 Transverse flow experiment conducted in flat matched die mold